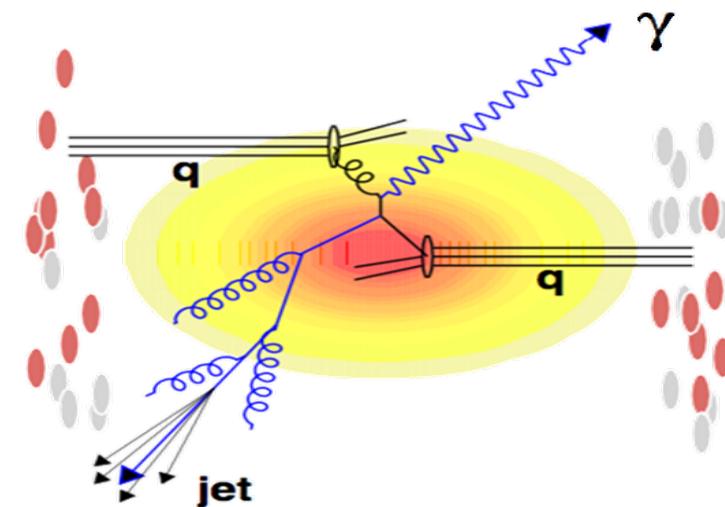


Jet Fragmentation in Vacuum and Medium

Outline

- Introduction to the QGP and jet quenching
- Part I: Jet Reconstruction in p+p and Cu+Cu
- Part II: Correlations with γ +jet events
in p+p and Au+Au
- Conclusions

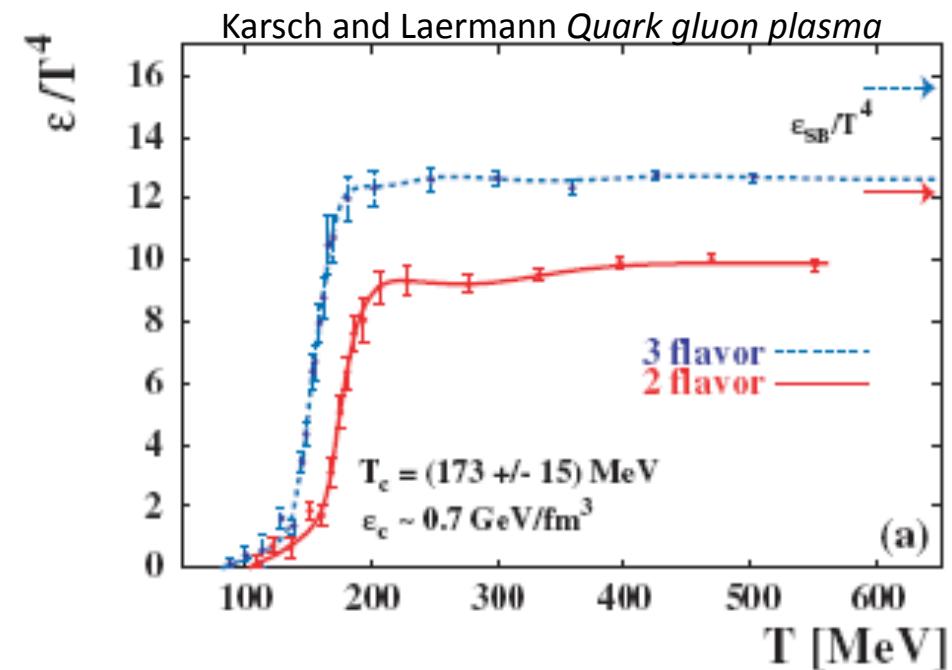
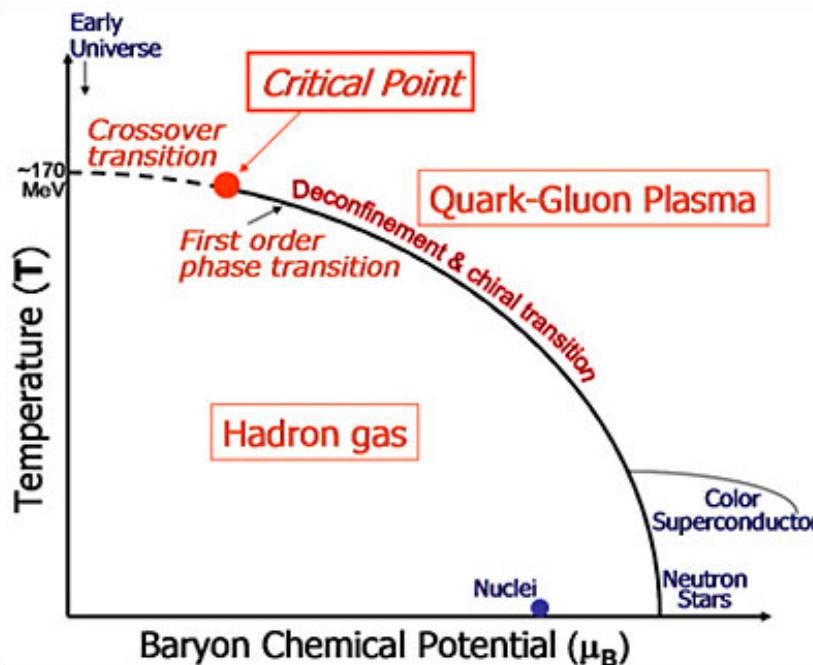


Matthew Nguyen
DIS 2010
April 21st, 2010



QGP Phase Transition

- Lattice predicts phase transition to color DOF at high T, ρ
- Critical Temperature ~ 170 MeV
- Heavy-Ion data indicates that produced matter:
 - Thermalizes rapidly
 - Exceeds the critical temperature
- An early prediction: Jet Quenching



Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

Abstract

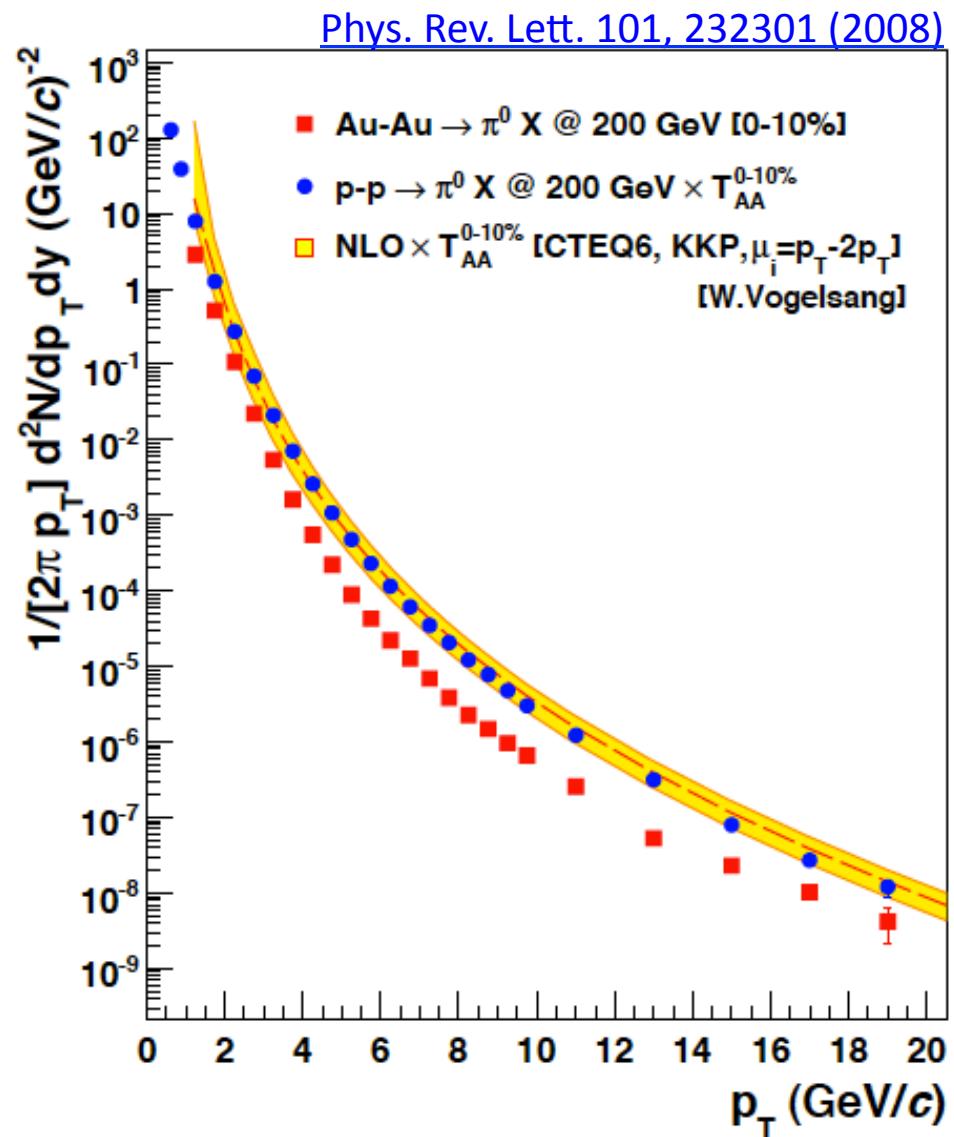
High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high- p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

High p_T suppression

- High $p_T \pi^0$ yield suppressed by 5x!
- Information integrated over:
 - Jet Energy
 - Production vertex / path-length
 - Evolution of system
(temperature, density)
- Radiative energy loss: $\Delta E \approx \hat{q} L^2$
- Naïvely, partons lose fraction of energy then fragment in vacuum:

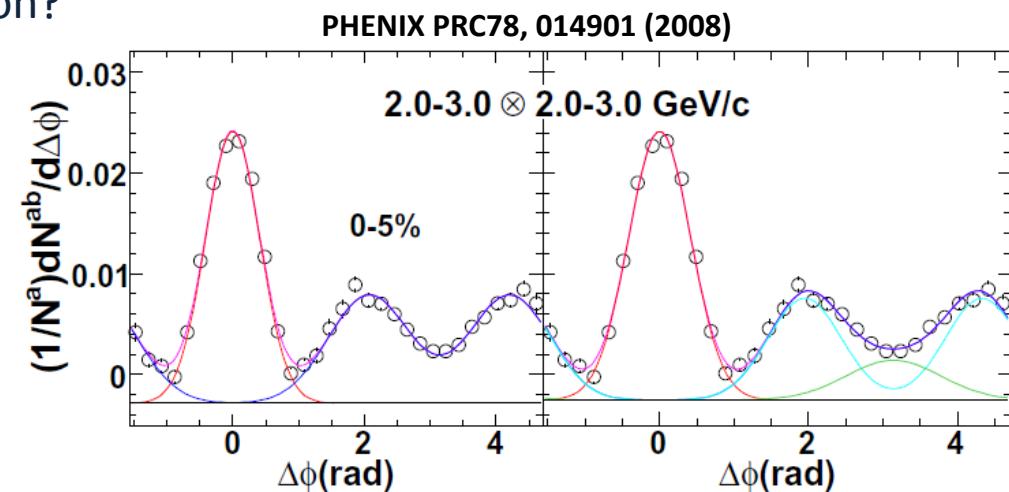
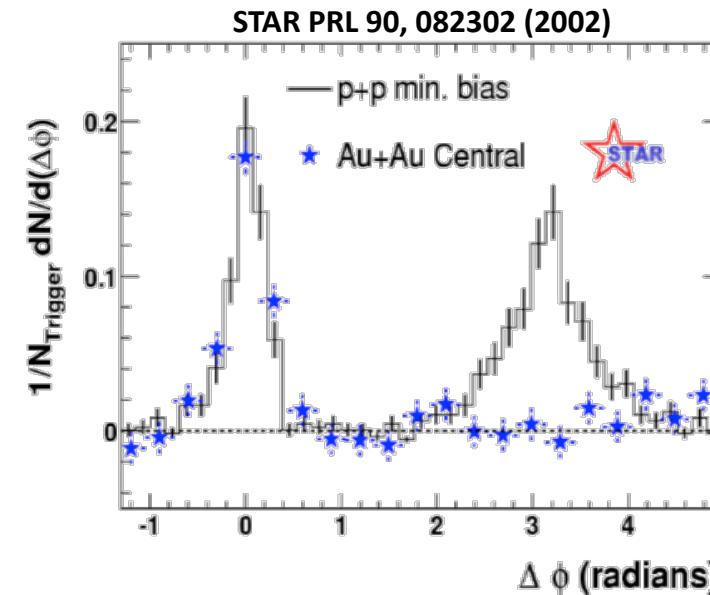
$$D^{\text{medium}}(z) = D \left(\frac{z}{1 - \Delta E / E} \right)$$

- Can we:
 - Determine properties of the medium, by measuring $\hat{q}(\vec{x}, t)$?
 - Learn something about QCD, by testing our understanding of parton energy loss?

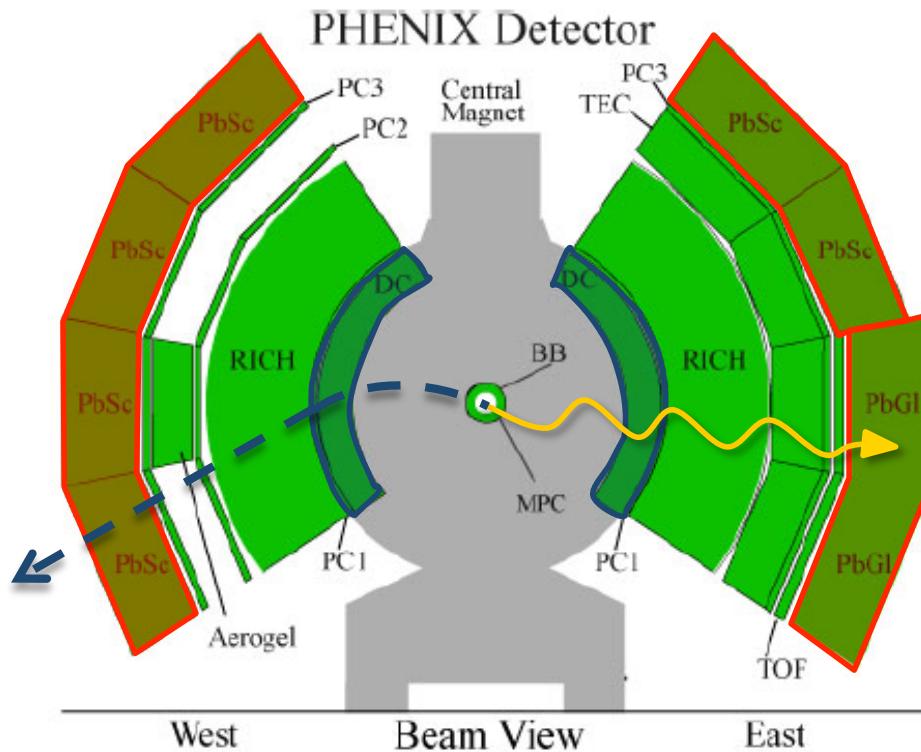


Back-to-Back Correlations

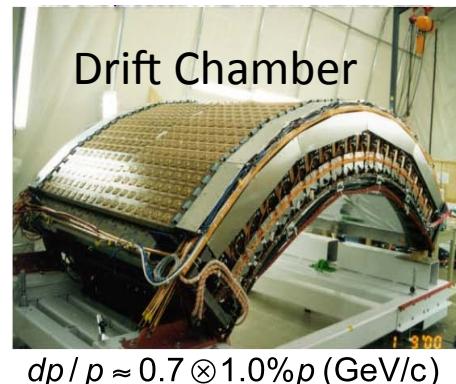
- For fractional E-loss expect shift of yield to low p_T and broadening of peak
- High p_T : Away-side jet disappears
- Modified Shape at Lower p_T : Reduced jet peak + large angle correlations?
- Are displaced peaks:
 - Medium response (e.g., a Mach cone)?
 - Medium-modified jet fragmentation?
- How can we tell the difference?
- Single, di-hadron difficult to model
Need observables where L and initial parton E unambiguous:
 - Fully reconstructed jets
 - Direct γ tagged jets, correlations



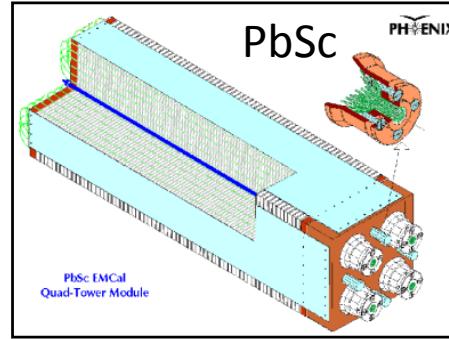
Photon-Hadron in PHENIX



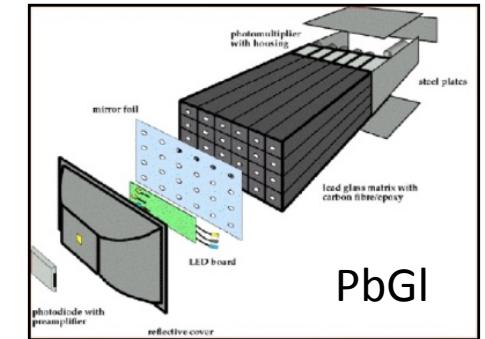
Charged Tracking:
Drift Chamber,
Pad Chambers



Electromagnetic Calorimeters



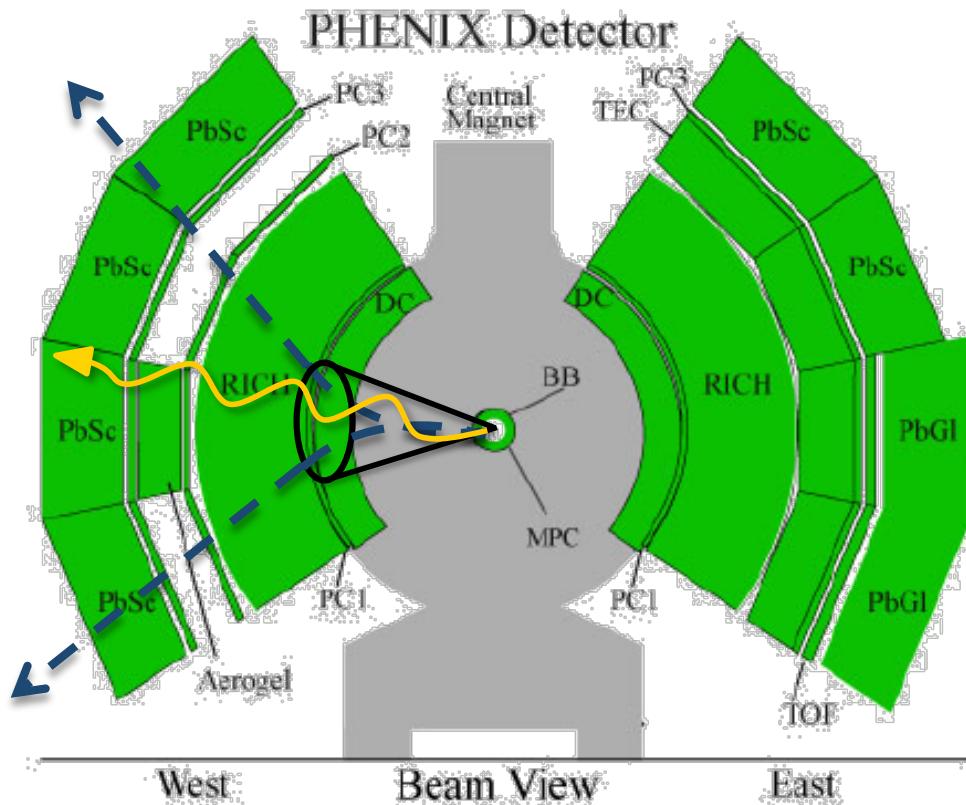
$$5.9/\sqrt{E(\text{GeV})} \oplus 0.8\%$$



$$8.1/\sqrt{E(\text{GeV})} \oplus 2.1\%$$

- π^0 photons separation out $p_T \sim 15 \text{ GeV}/c$
- Hadron rejection w/ shower shape, track veto
- High $p_T \gamma$ triggering
- Charged Particle momentum from DC/PC1
- Matching to outer PC's rejects secondaries
- $e^{+/-}$ ID w/ RICH, E/p
- BBC, ZDC: MB trigger, vertex, centrality

Jets in PHENIX



Jets measured from charged tracks and EMCal clusters

- ✗ No hadronic calorimetry
- ✗ Small acceptance for jets ($|\eta| < 0.35$)
- ✓ Small material budget
- ✓ Good tracking, EMCal resolution, electron ID → no double counting of energy

Part I: Jet Reconstruction

Gaussian Filter Algorithm

Authors:
Y.S. Lai, B.A. Cole

arxiv:0806.1499

1. Define p_T weighted particle density

$$p_T(\eta, \phi) = \sum_{i \in \text{particles}} p_{T,i} \delta(\eta - \eta_i) \delta(\phi - \phi_i) - p_{T,\text{BG}}(\eta, \phi)$$

2. Subtract mean particle density (for heavy-ion collisions)
3. Calculate filter weighted density at each point

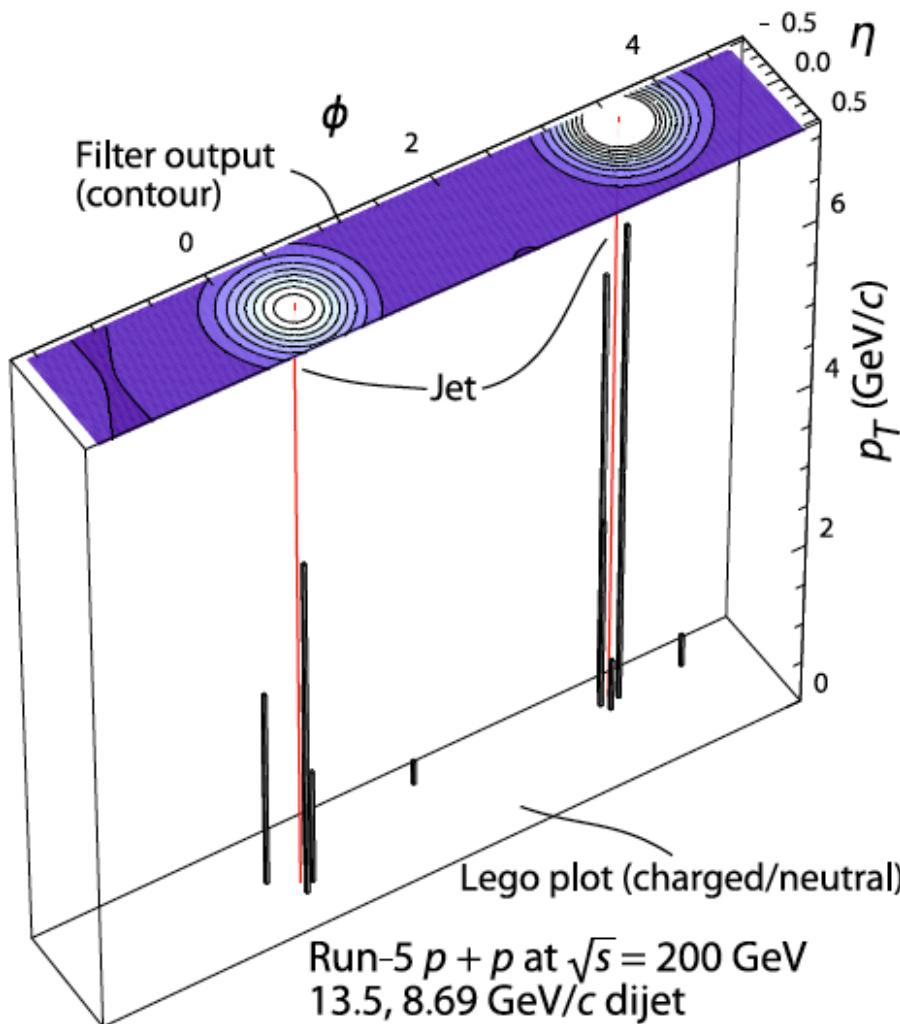
$$\tilde{p}_T(\eta, \phi) = \iint d\eta' d\phi' p_T(\eta', \phi') h(\eta - \eta', \phi - \phi')$$

4. Taking the filter function to be a Gaussian

$$h_\sigma(\eta, \phi) = \exp\left[-\frac{\eta^2 + \phi^2}{2\sigma^2}\right]$$

5. Jets correspond to maxima of the filter weighted density
6. Estimate the jet direction from the discrete filter response

Gaussian Filter Jets

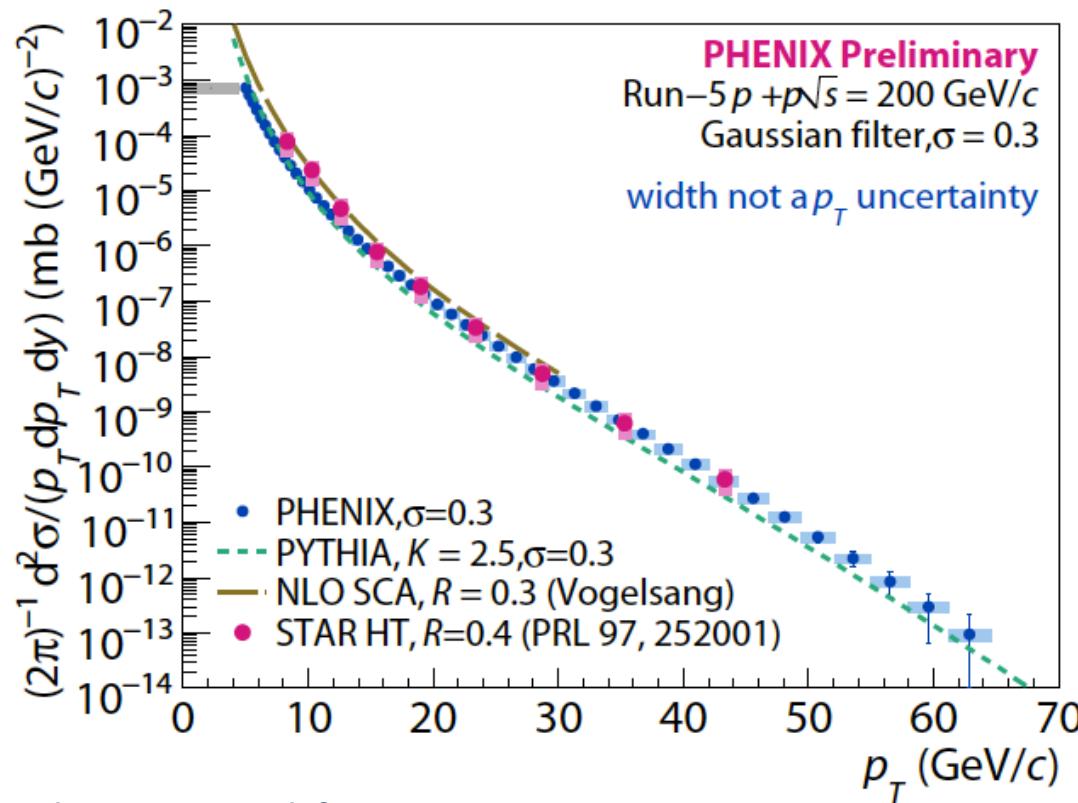


- Cone-like, but w/o merge/split
- Seedless
- Infrared/collinear safe
- Gaussian response
 - Improves discrimination from soft background
 - Diminishes impact of finite acceptance
- Motivated by energy-flow observables

Berger et al, PRD68:014012(2003)

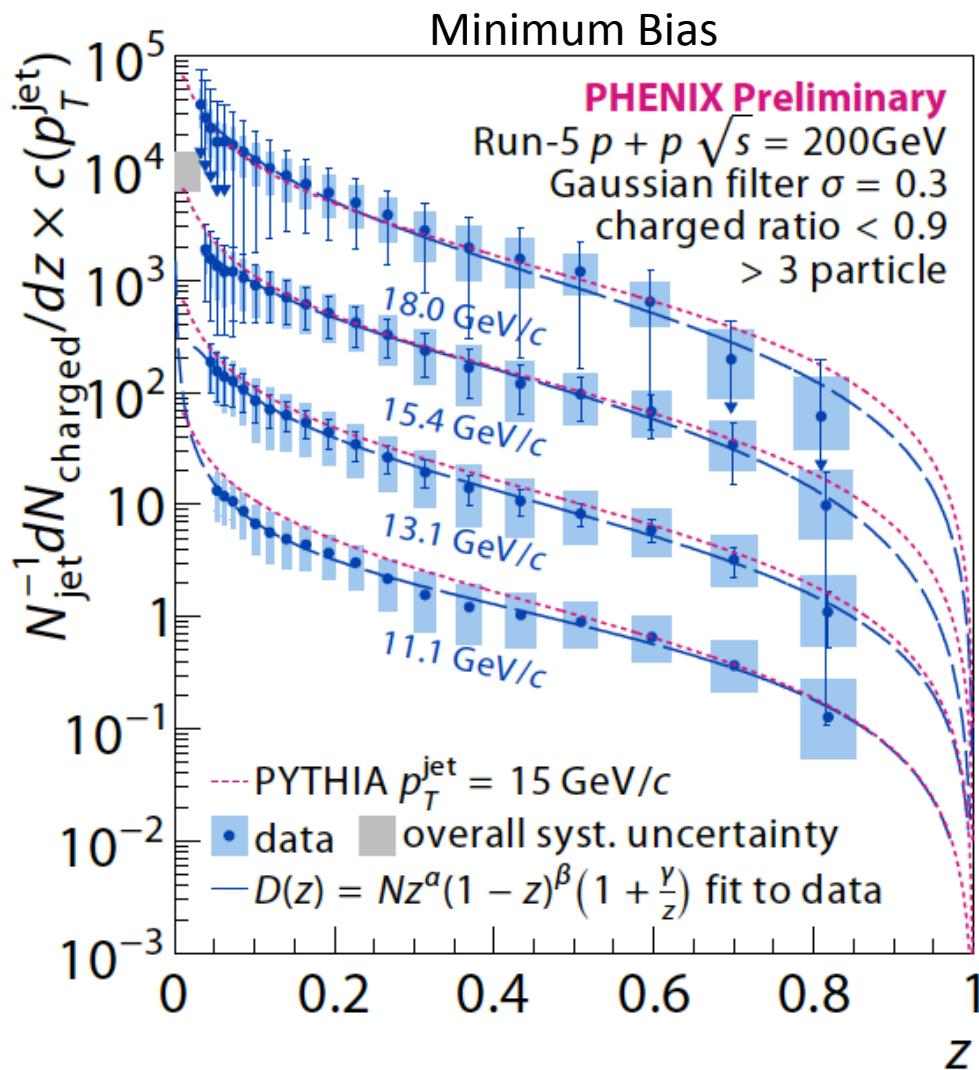
See arxiv:0806.1499 for comparisons to standard jet algorithms

p+p Inclusive Jet Cross Section



- Jet energy scale determined from PYTHIA + GEANT
- p_T reach out to large x (~ 0.6)
- Systematics from calo. energy scale, trigger efficiency, conversions ($p_T > 20 \text{ GeV}/c$)
- Consistent with STAR using mid-point cone algorithm with $R = 0.4$
- Compares reasonably well to theory, neither PYTHIA nor SCA an exact comparison

Charged Hadron FF (p+p)



- Cuts to avoid conversions, calorimeter noise, upstream interactions:
 - # of particles > 3
 - charged fraction < 0.9
 - $z < 0.85$
- Resulting jet selection bias contained in systematics
- Consistent with PYTHIA, FF scaling

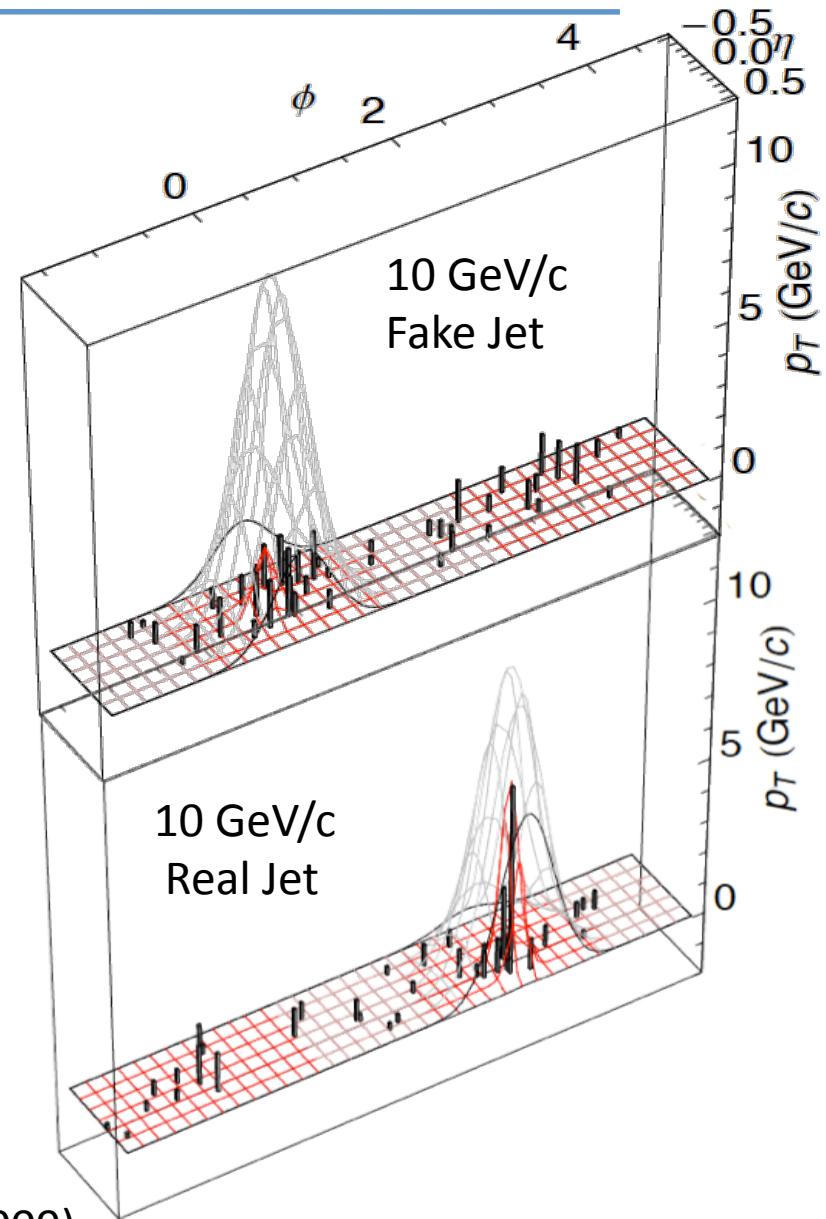
Jet Filtering in Heavy-Ion Collisions

- Central HI events are dominated by soft particle production
- The mean background level is subtracted

$$p_T(\eta, \phi) = \sum_{i \in \text{particles}} p_{T,i} \delta(\eta - \eta_i) \delta(\phi - \phi_i) - p_{T,BG}(\eta, \phi)$$

but fluctuations give fake jets until large jet p_T

- Angular weight from Gaussian filtering helps to discriminate against background
- Additional fake rejection is required



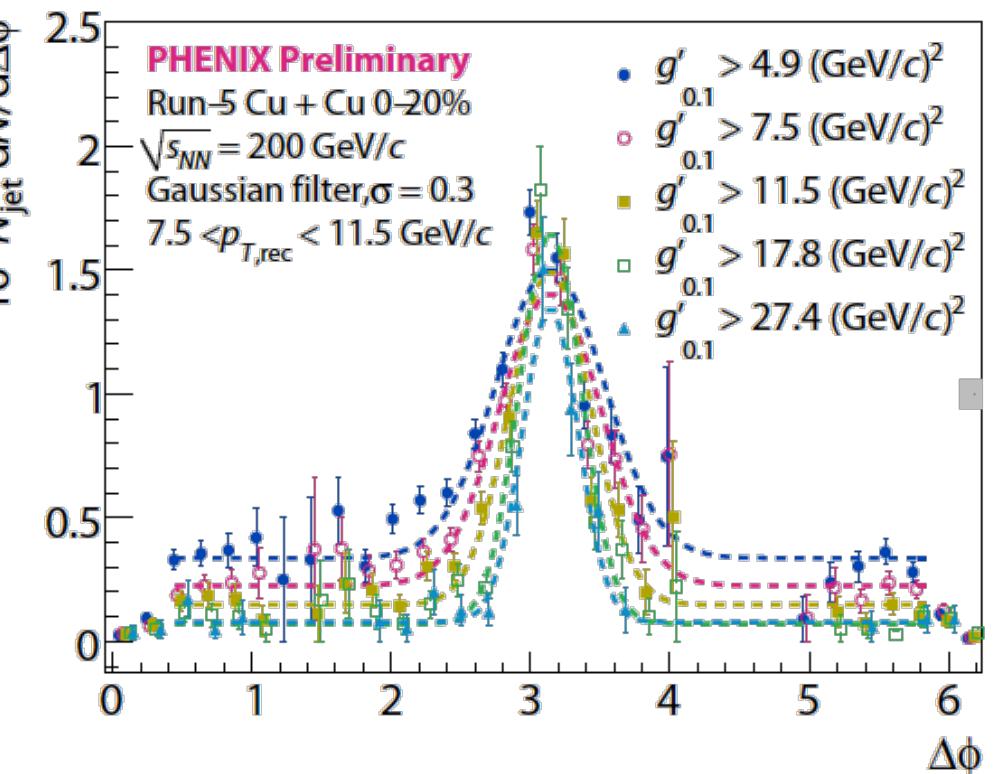
More on fake jets in HI, see Grau et al., EPJC62:191 (2009)

Fake Rejection in Heavy-Ion

- Discriminate background by requiring well-collimated jets
- Use Gaussian weighted p_T^2 sum:

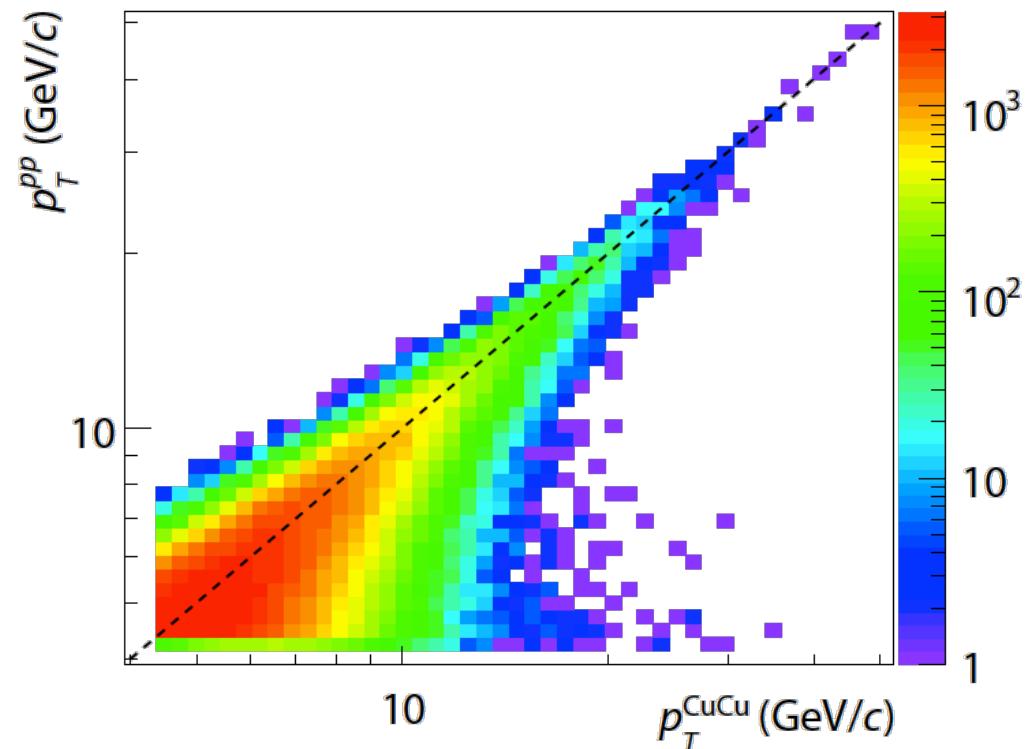
$$g_{\sigma_{\text{dis}}}(\eta, \phi) = \sum_{i \in \text{particles}} p_{T,i}^2 \exp \left[-\frac{(\eta_i - \eta)^2 + (\phi_i - \phi)^2}{2\sigma^2} \right]$$

- Small width of $\sigma_{\text{dis}} = 0.1$ chosen
- Use $\Delta\phi$ between jets as a metric
- Vary $g_{0.1}$ until intra-jet pedestal becomes stationary
- Used $g_{0.1} > 17.8 \text{ (Gev/c)}^2$
- Fake rate $< 10\%$ for jet $p_T < 7.5 \text{ GeV}/c$

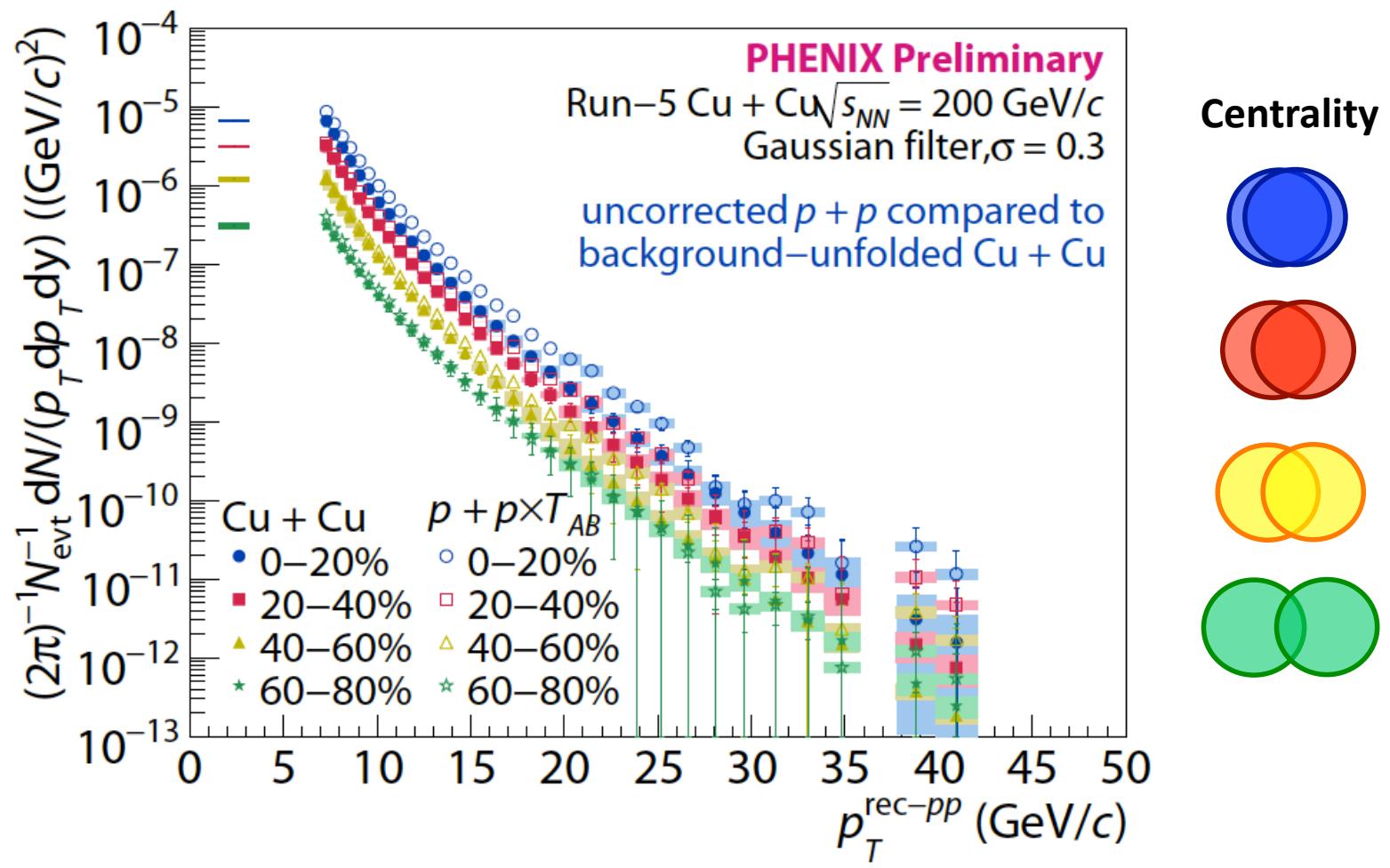


Background Unfolding in Cu+Cu

- Effect of background on JES determined by embedding p+p jets into Cu+Cu events
- Embedded jets matched to input to avoid Cu+Cu jets
- Efficiency $\rightarrow 1$ at $p_T \sim 12$ GeV/c
- Background smears jets towards larger p_T

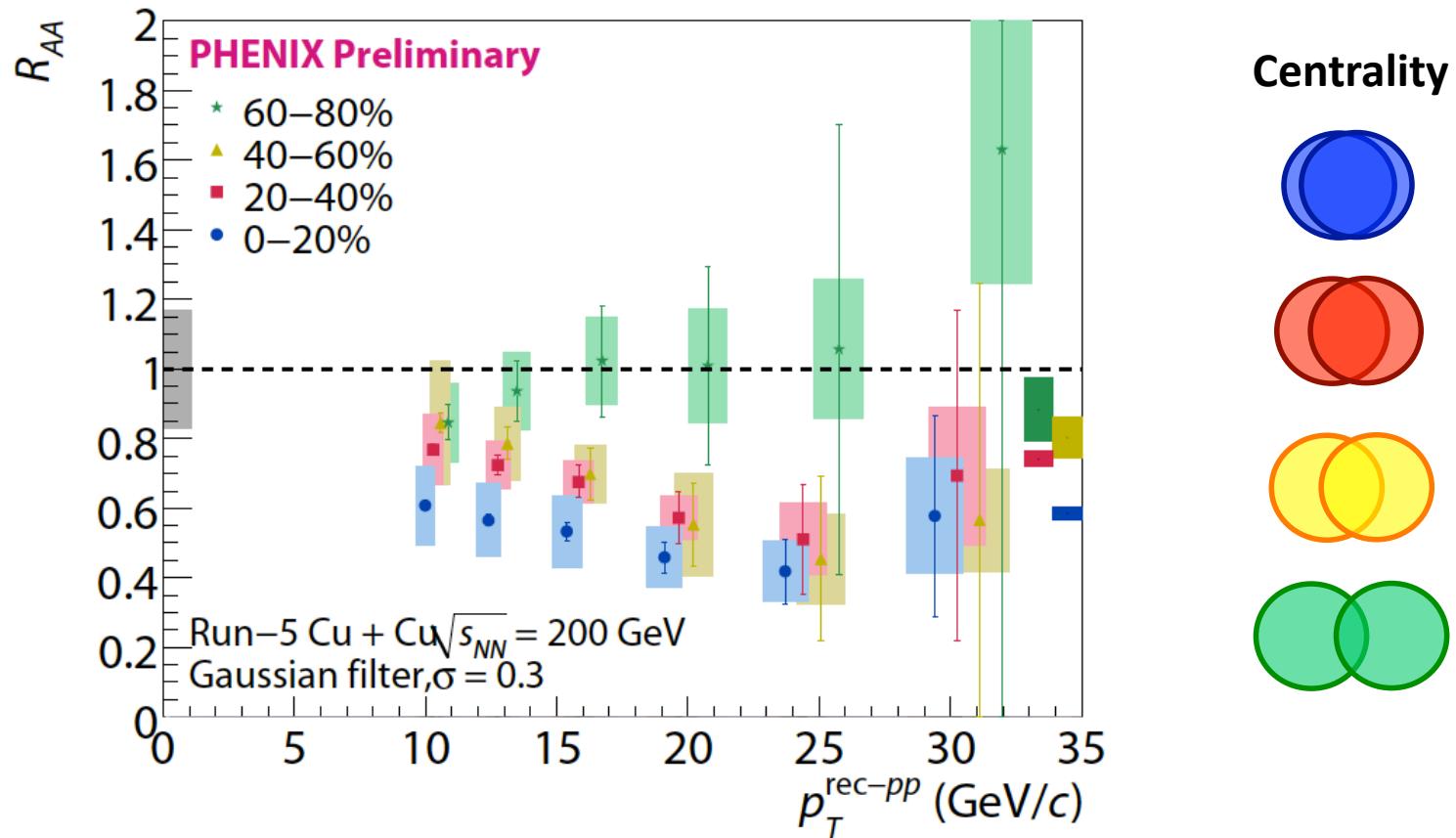


Jet Spectra in Cu+Cu



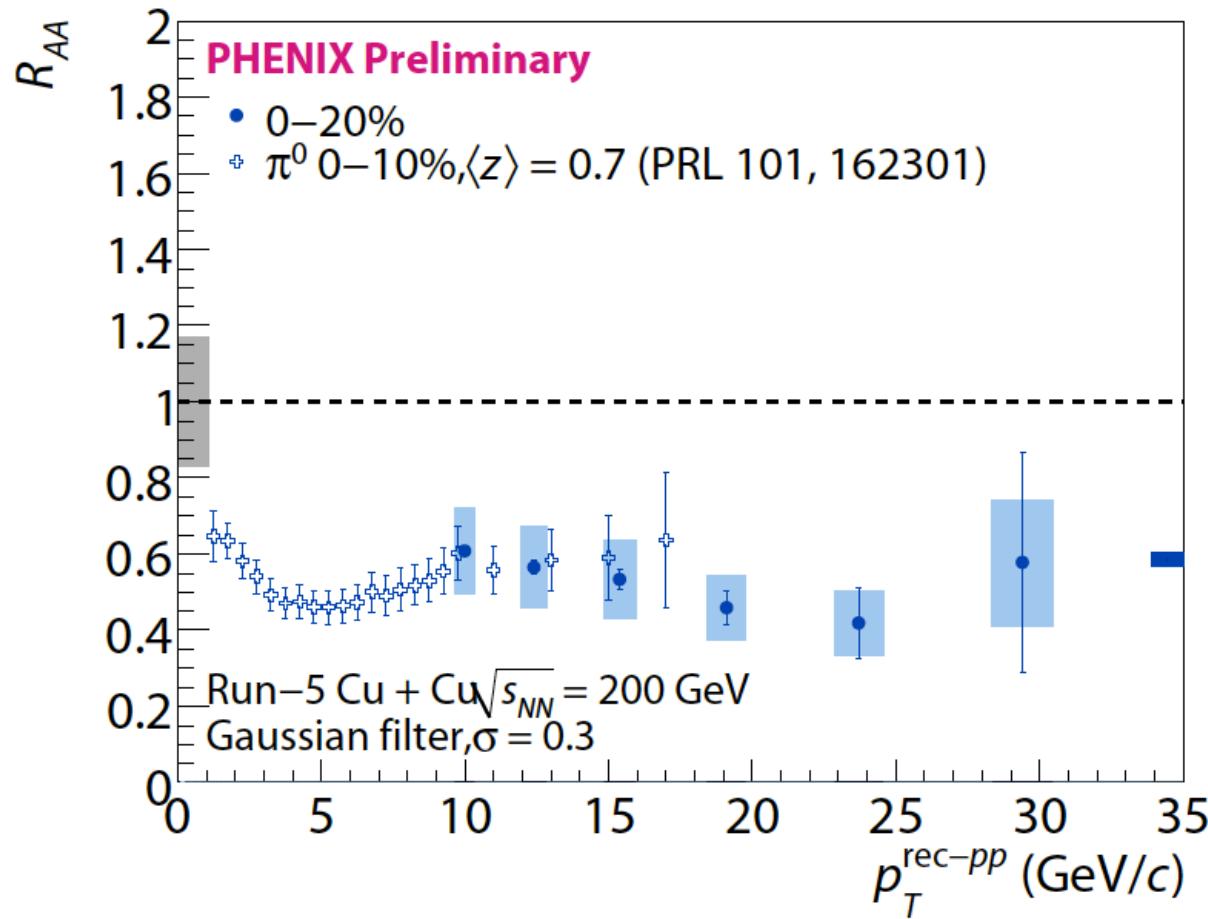
- Uncorrected $p+p$ jets (scaled by T_{AB}) compared to background-unfolded Cu+Cu jets
- Additional systematics from different energy scale, acceptance between $p+p$ and Cu+Cu

Nuclear Modification (R_{AA}) of Jets



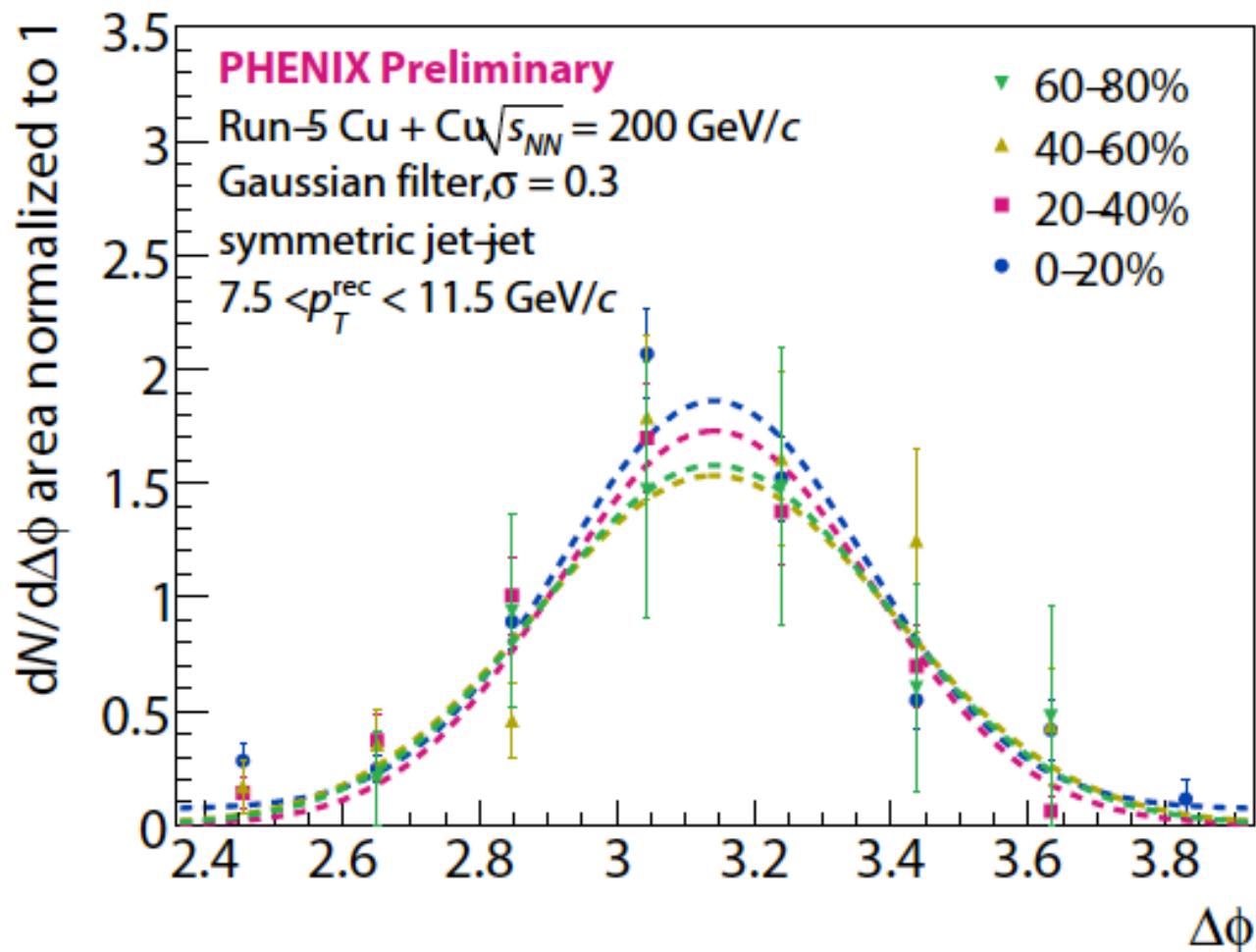
- Jet yield suppressed in central (head-on) collisions
- Effect disappears from as collisions become more peripheral
- Not energy scale corrected, but R_{AA} nearly flat

Jet vs. Single Hadron R_{AA}



- No significant energy dependence out to 30 GeV/c
- Data indicate that quenched jets are not recovered by Gaussian filter

Jet-Jet Correlations

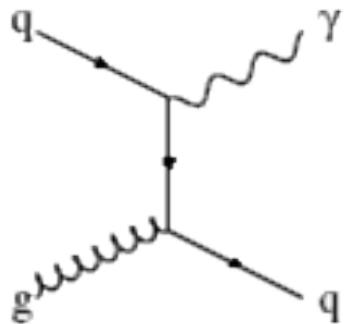


- Azimuthal correlations between symmetric jet pairs
- No significant jet broadening or displacement observed

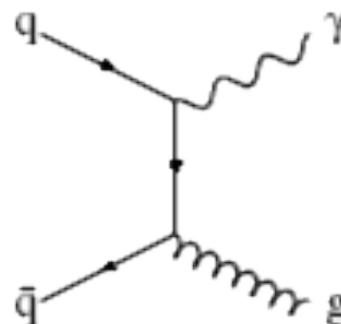
Part II: Direct γ Correlations

Direct γ 's at LO

Compton

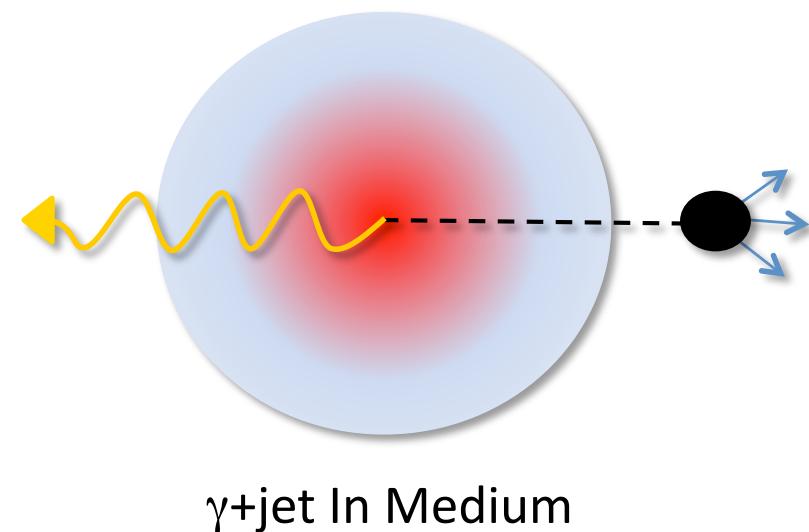
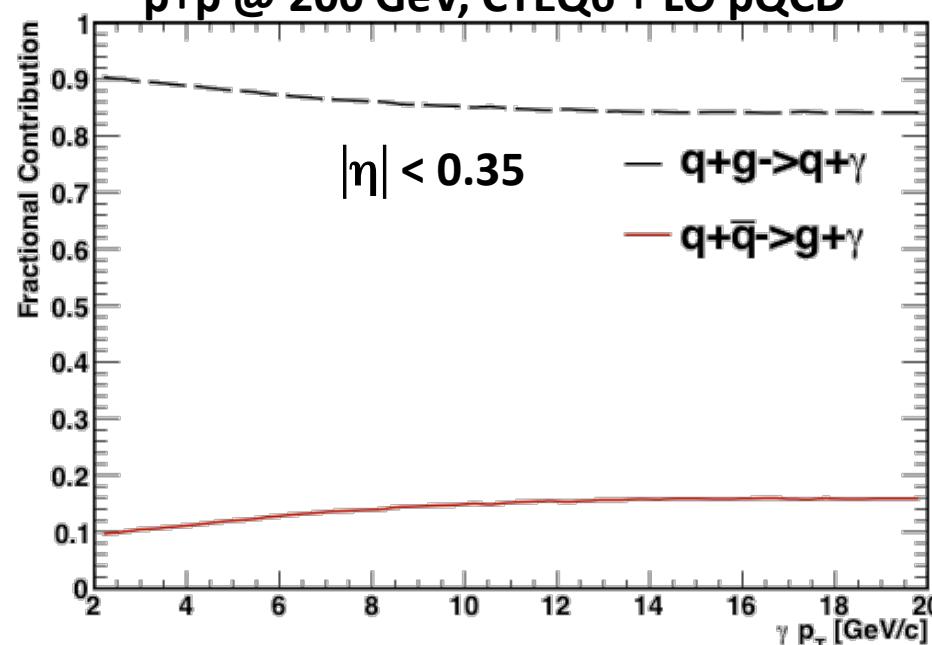


Annihilation



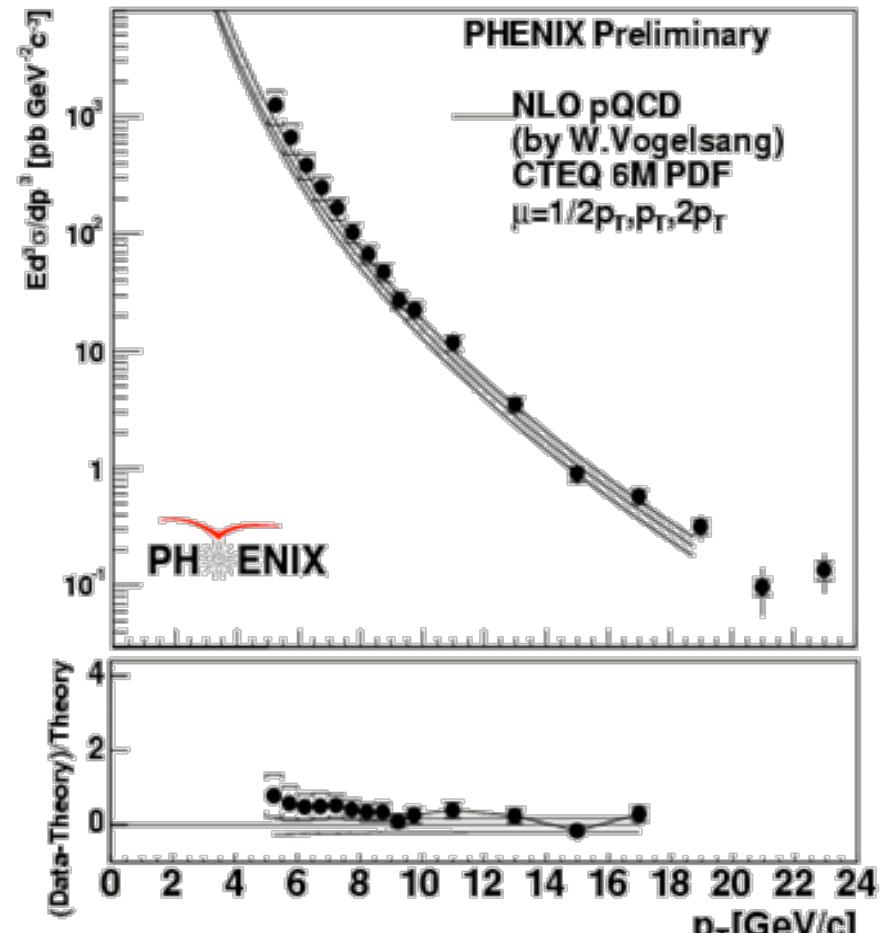
- Compton scattering dominant
- Transparent to medium
- $\gamma p_T = \text{recoil parton } p_T$ (before E-loss)
- Use direct γ to tag unbiased jets
 - Map the medium with direct γ triggered jets (Jet tomography)
 - Use γ energy to construct (modified) FF

p+p @ 200 GeV, CTEQ6 + LO pQCD



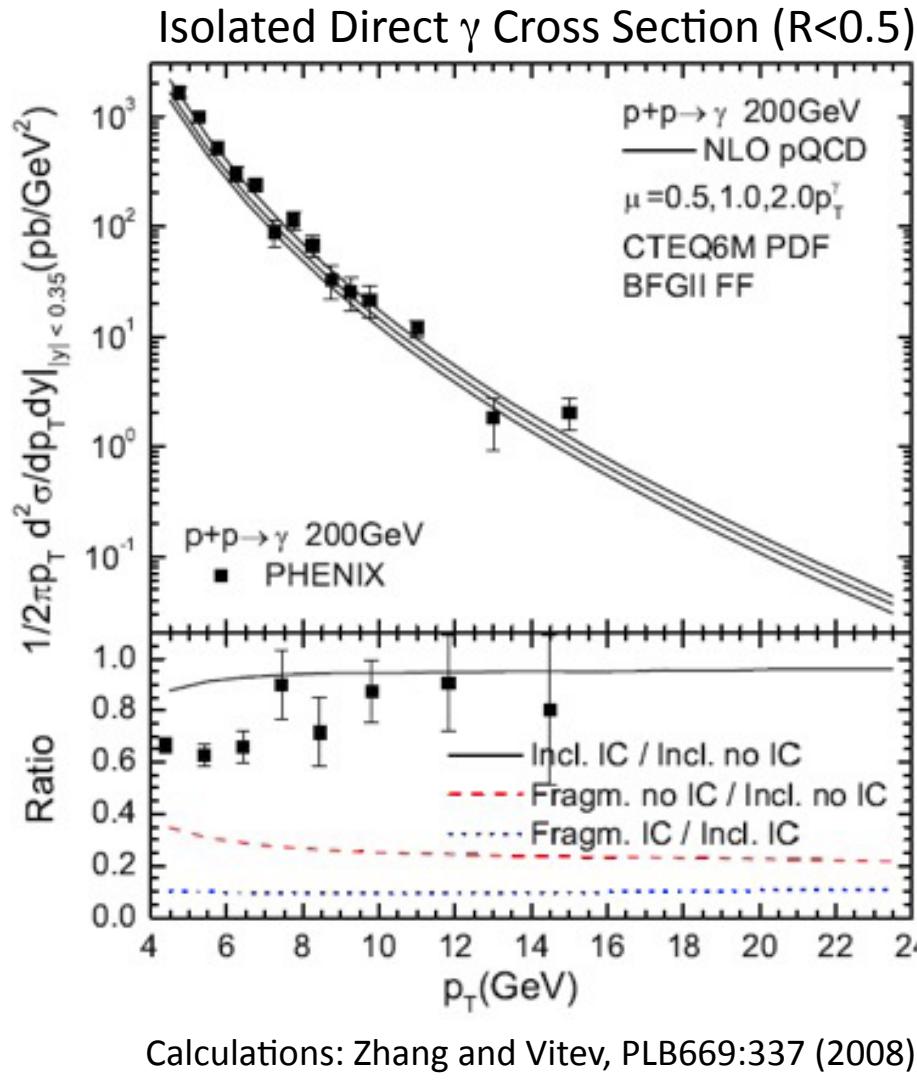
Inclusive Direct γ 's

- PHENIX can measure inclusive direct γ 's
→ no isolation requirement
- Important b/c isolation challenging in heavy-ions

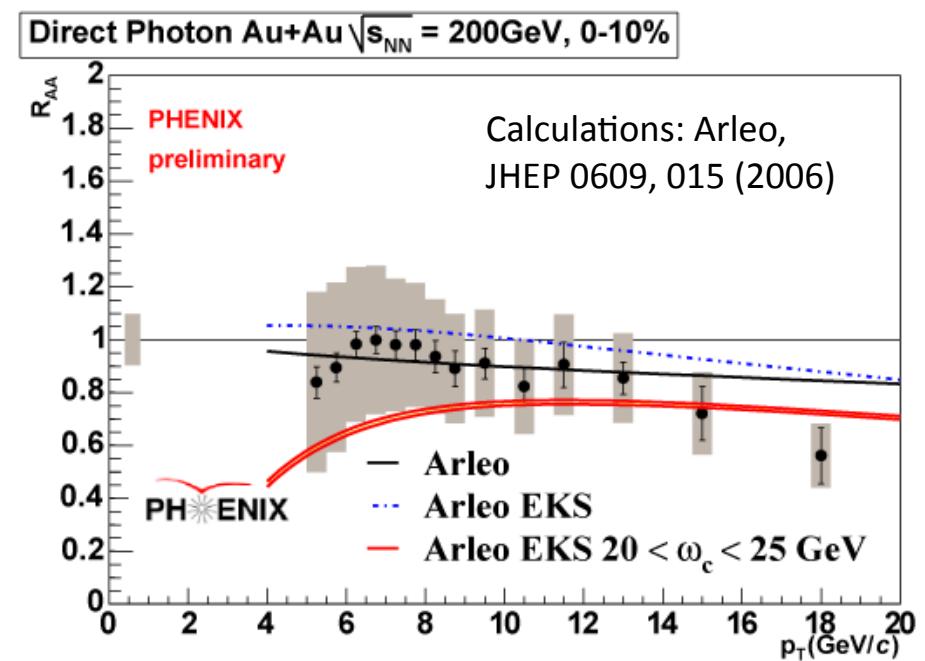


Inclusive Direct γ Cross Section in $p+p$

Beyond Leading Order



- Fragmentation γ 's
 - Spoil momentum balance
 - Biased by E-loss
- Also k_T effect
- Medium-Induced γ sources?



Direct γ -h by Statistical Subtraction

- Construct correlations of γ 's with hadrons

$$Y_{\text{total}} = \frac{\# \text{ of photon - hadron pairs}}{\# \text{ of photons}}$$

- Contains a contribution from direct and decay sources

$$Y_{\text{total}} = \frac{N_{\text{direct}}}{N_{\text{total}}} Y_{\text{direct}} + \frac{N_{\text{decay}}}{N_{\text{total}}} Y_{\text{decay}}$$

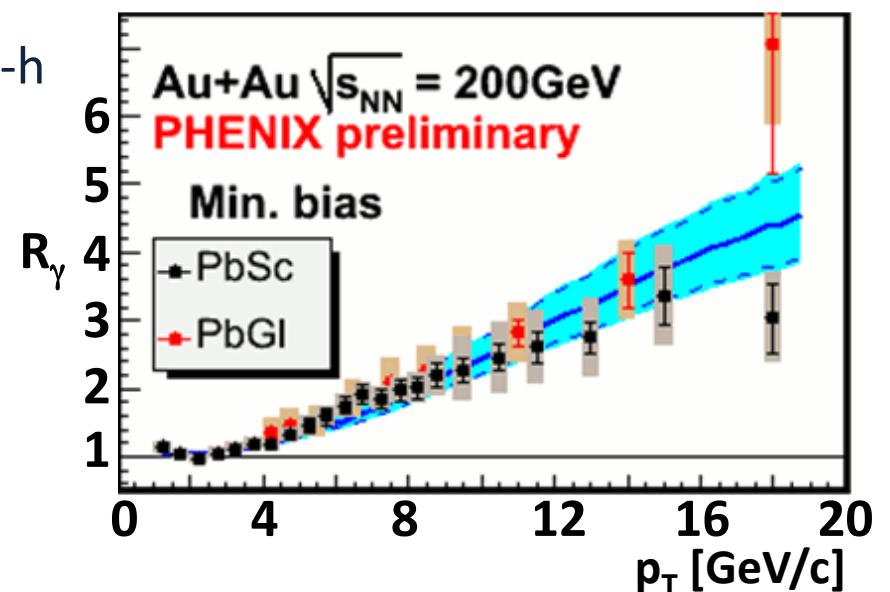
$$R_{\gamma} = \frac{\text{total } \# \text{ of } \gamma's}{\# \text{ of decay } \gamma's}$$

- *Estimate decay contribution from π^0 -h, η -h (see next slide)

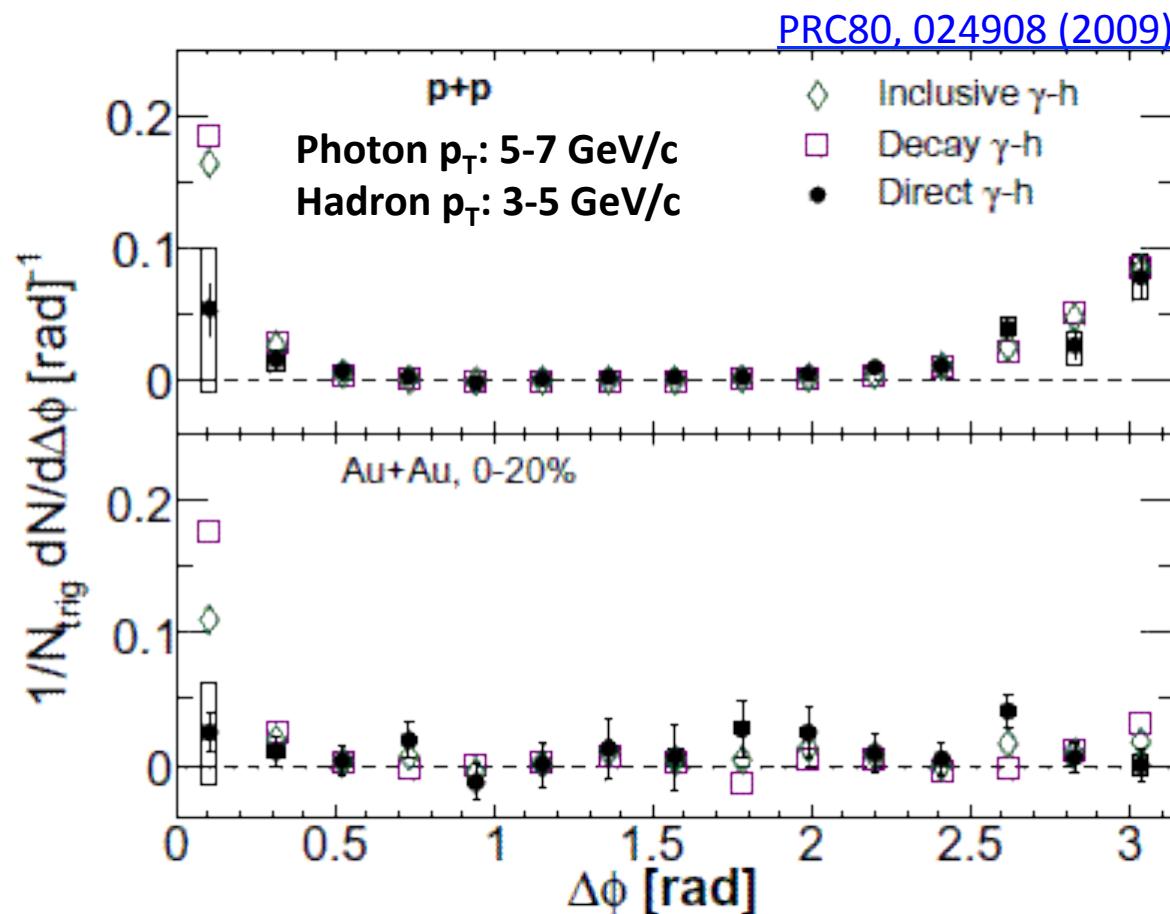
- Solve for Y_{direct} , using measured R_{γ}

$$Y_{\text{direct}} = \frac{R_{\gamma}}{R_{\gamma} - 1} Y_{\text{total}} + \frac{1}{R_{\gamma} - 1} Y_{\text{decay}}$$

*Non-trivial, for details: [PRC80, 024908 \(2009\)](#)



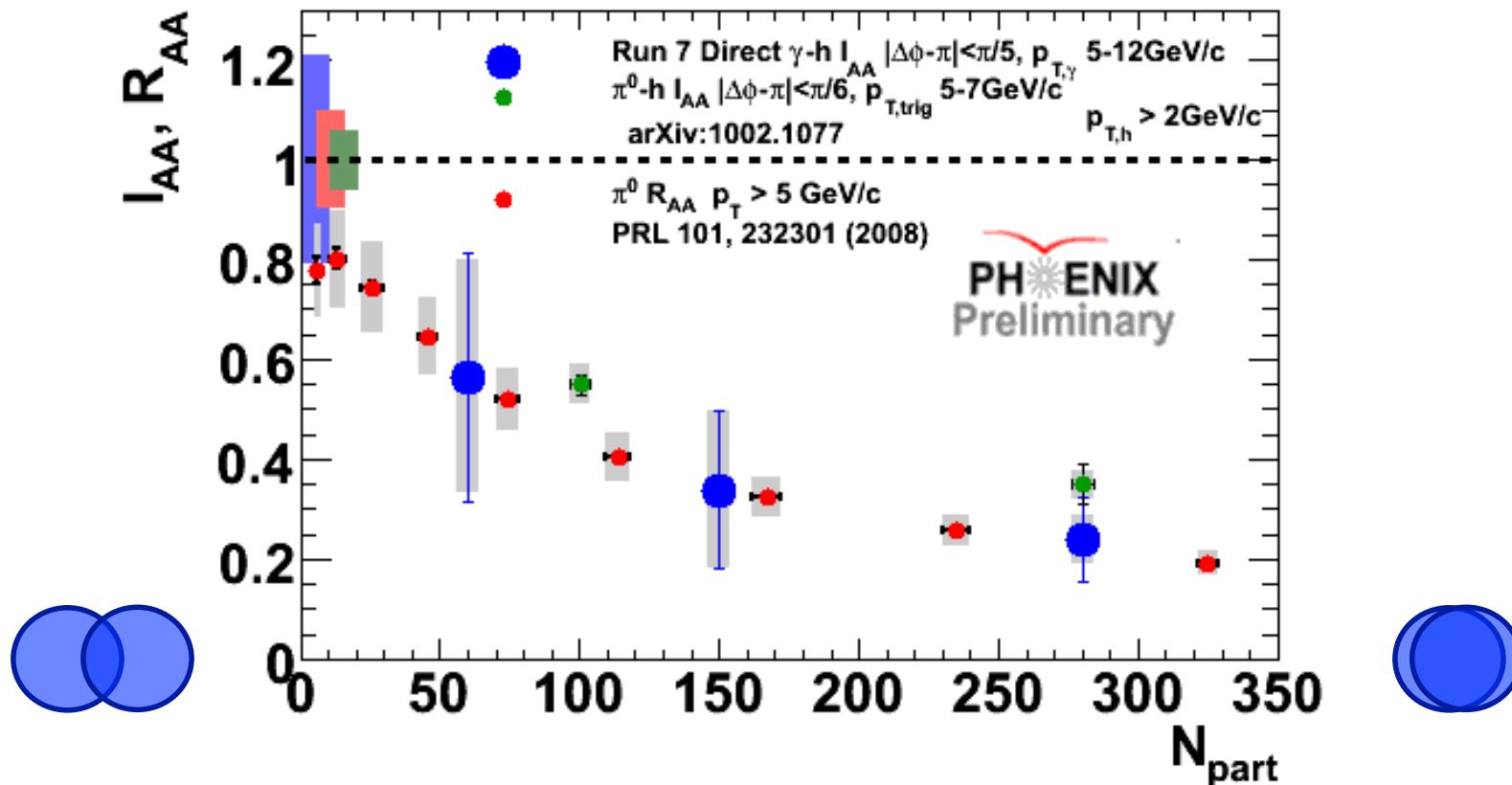
Direct γ Correlations



- ✓ No significant near-side correlation
- ✓ Disappearance of back-to-back correlations in Au+Au

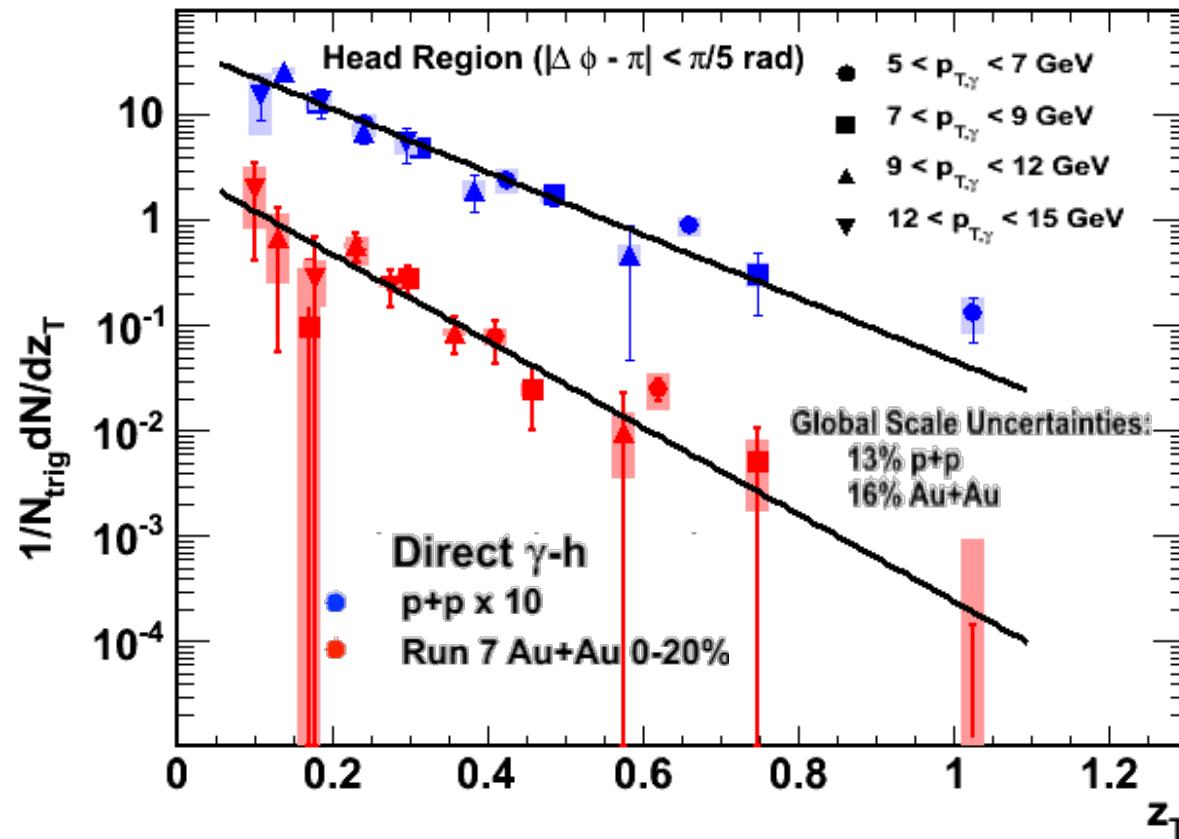
Suppression for γ -Jets

I_{AA} = hadrons per photon in Au+Au / hadrons per photon in p+p



- Direct γ -h should sample different path-length than single, di-hadrons
- Similar suppression within large uncertainties
- Note angular range only $| \Delta\phi - \pi | < \pi/6$, would not include displaced peaks

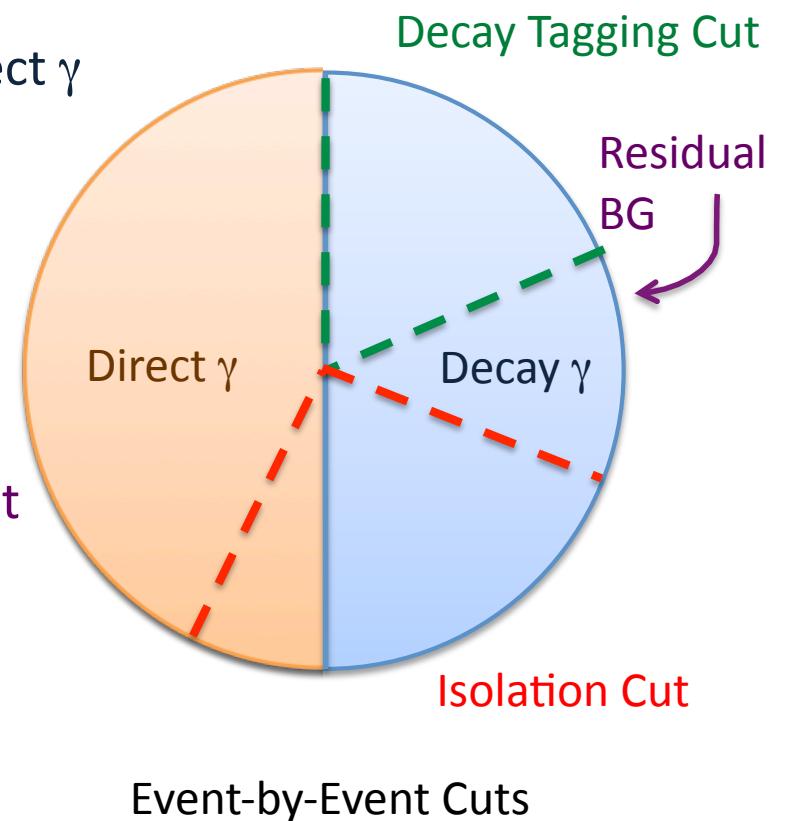
Modified Fragmentation?



- $z_T = \text{hadron } p_T / \text{photon } p_T$
- Again, note restricted angular range
- Steeper slope in central Au+Au, but only 1.3σ statistical significance
- How to reduce uncertainties?

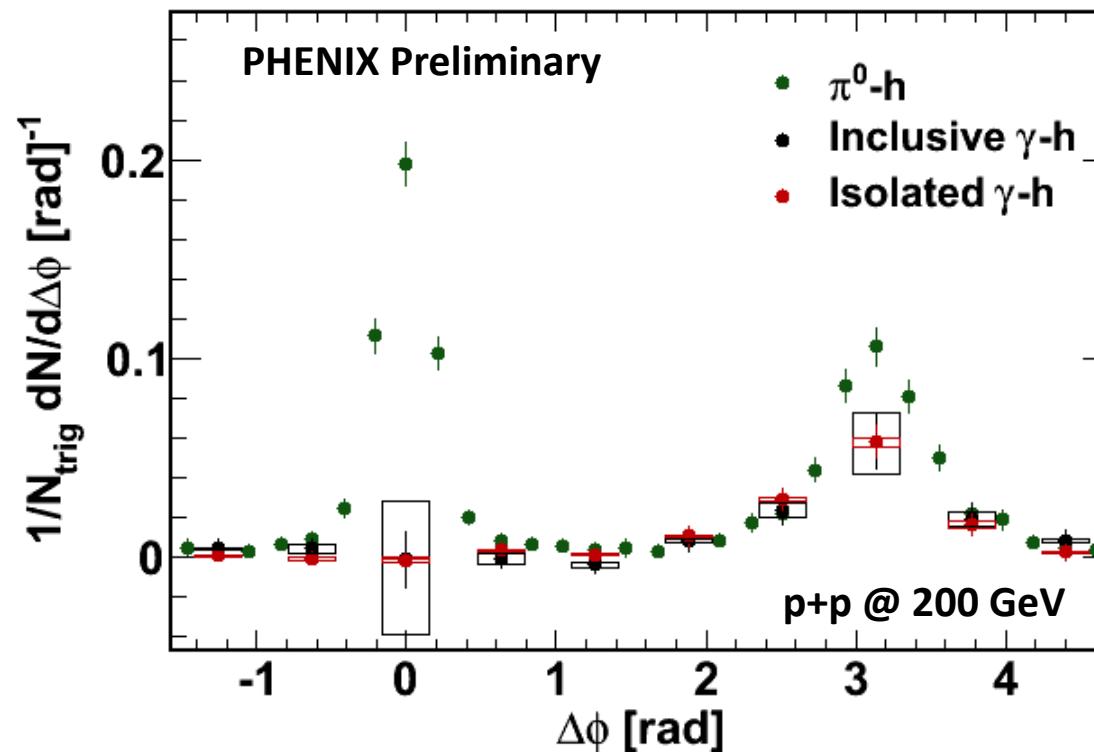
Event-by-Event Direct γ ID

- Large uncertainties due to statistical subtraction
- Large background in heavy-ions complicates direct γ ID on a per-event basis
- As a start, we can test methods in p+p:
 - Tag decay pairs by invariant mass
 - Require photon isolation
- Due to finite acceptance/efficiency must subtract residual decay from un-tagged, isolated mesons
- Requires estimate of efficiencies from
 - Decay Tagging: From invariant mass distributions
 - Isolation: From isolation efficiency of decay sources



Isolated Direct γ Correlations

Isolation cut : Sum of charged momentum + neutral energy
within cone of $R = 0.5 < 10\%$ of the photon energy



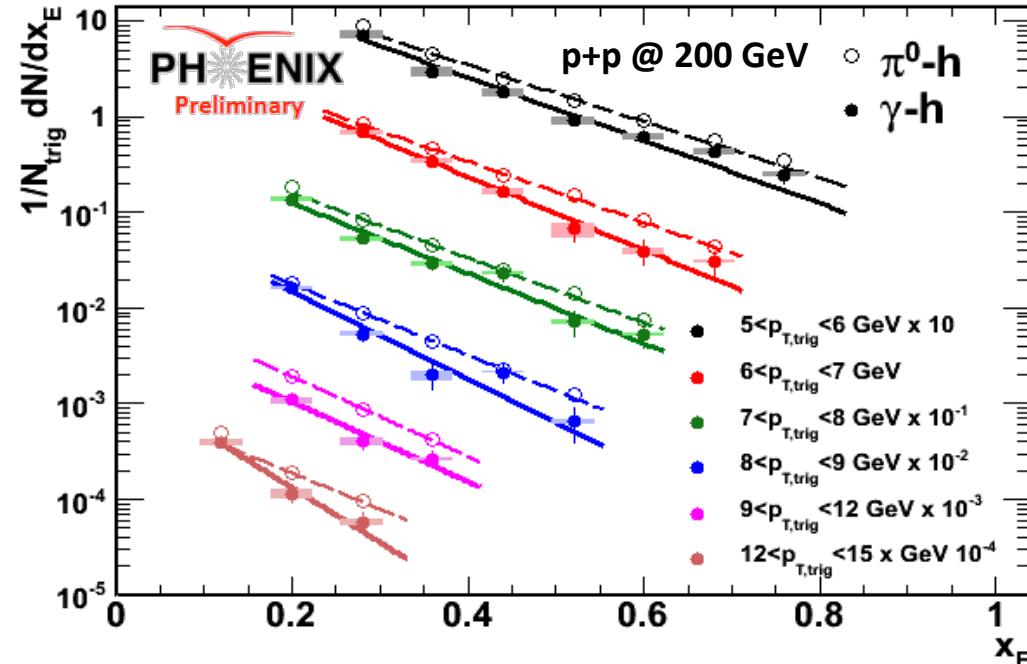
Application of isolation cut and decay photon tagging →
Drastically reduced systematic and statistical uncertainties on $\gamma\text{-}h$ correlations

γ Triggered “FFs”

$$x_E = \frac{p_{T,\text{hadron}}}{p_{T,\text{photon}}} |\cos \Delta\phi|$$

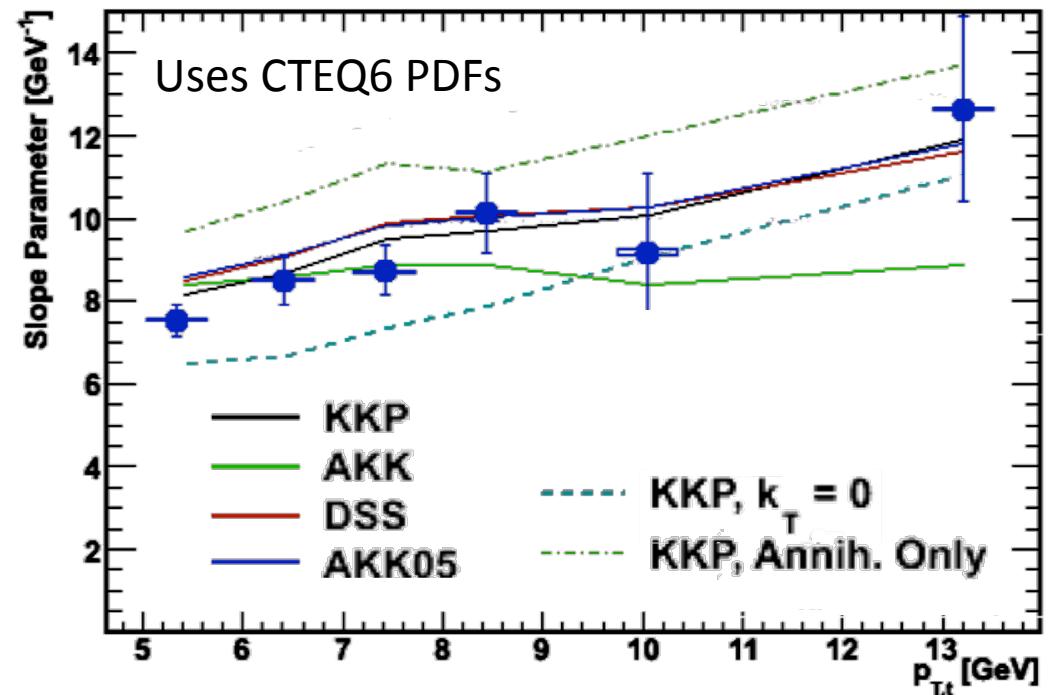
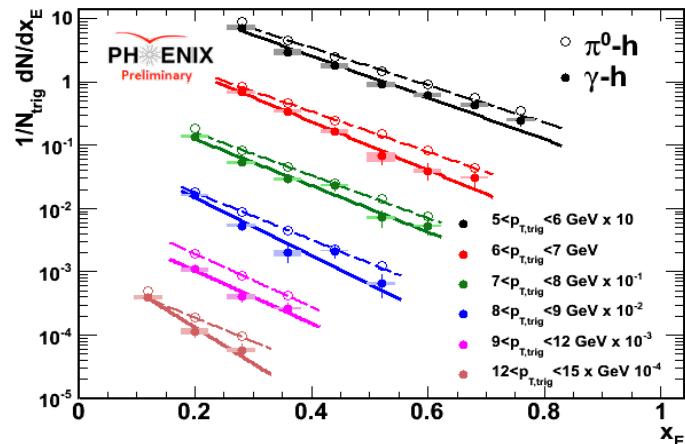
$$x_E \approx z$$

for $p_{T,\text{photon}} = p_{T,\text{jet}}$



- At LO x_E distribution is equivalent to the FF
- Expect to dominant contribution to be from valence up quarks
- k_T comparable to γp_T , breaks FF scaling
- Simple test: Apply Gaussian k_T smearing to LO and check that FF is recovered

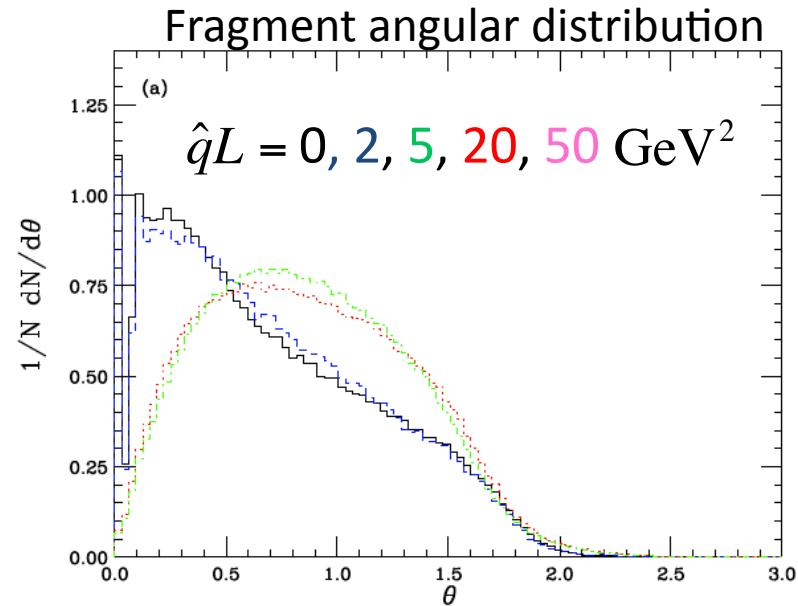
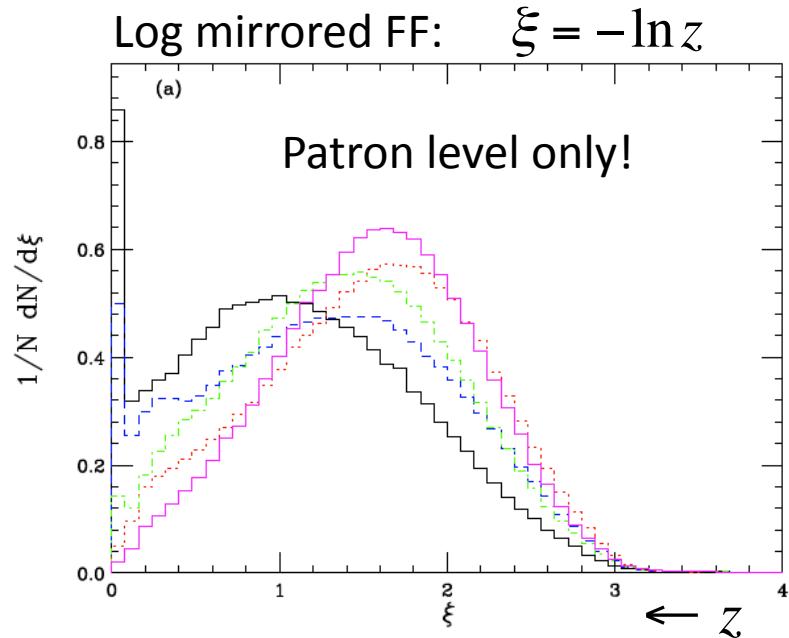
From γ Triggered x_E to the FF



- $k_T = 0$ calculation harder than data
- $\langle k_T \rangle$ determined from pout distributions (See [PRD74, 072002 \(2006\)](#) and forthcoming article)
- k_T -smeared LO reproduces data independent of choice of FF fit (KKP, AKK, DSS)
- Annihilation process only (i.e. gluon fragmentation) gives a much steeper slope
→ data sensitive to quark vs. gluon FFs
- Isolated γ -h a well understood baseline, now we need to measure it in Au+Au

Prologue: Modified Shower Evolution

Armesto, Corcella, Cunqueiro and Salgado JHEP 0911:122,2009



- Models moving beyond fraction E-loss picture towards more complete description of in-medium parton showers
- Modified splitting kernels in DGLAP evolution; predicts:
 - Enhanced yield at very low z $\xi = 2 \rightarrow z \approx 0.135$
 - Large angle radiation
- Implies novel regime in which QCD radiation is drastically altered, but
 - Experimentally challenging to measure small z , large angle
 - How do differentiate from possible medium response mechanisms?

Conclusions

- Medium effects on jet production have been studied using fully reconstructed jets and direct γ triggered correlations
- Both Jet and Direct γ data demonstrate quenching
- However, no broadening of correlations or modified fragmentation is apparent within the restricted ranges of these measurements
- This provides stringent constraints and models and, hopefully, medium properties if the data can be modeled
- Where does the energy go?
 - To large angle outside of the jet cone?
 - To low z where data uncertainties are large?
- QCD may demonstrate novel phenomenon as data provides more energetic probes and hotter, denser matter

More From Bjorken

7. Why is any of this interesting?

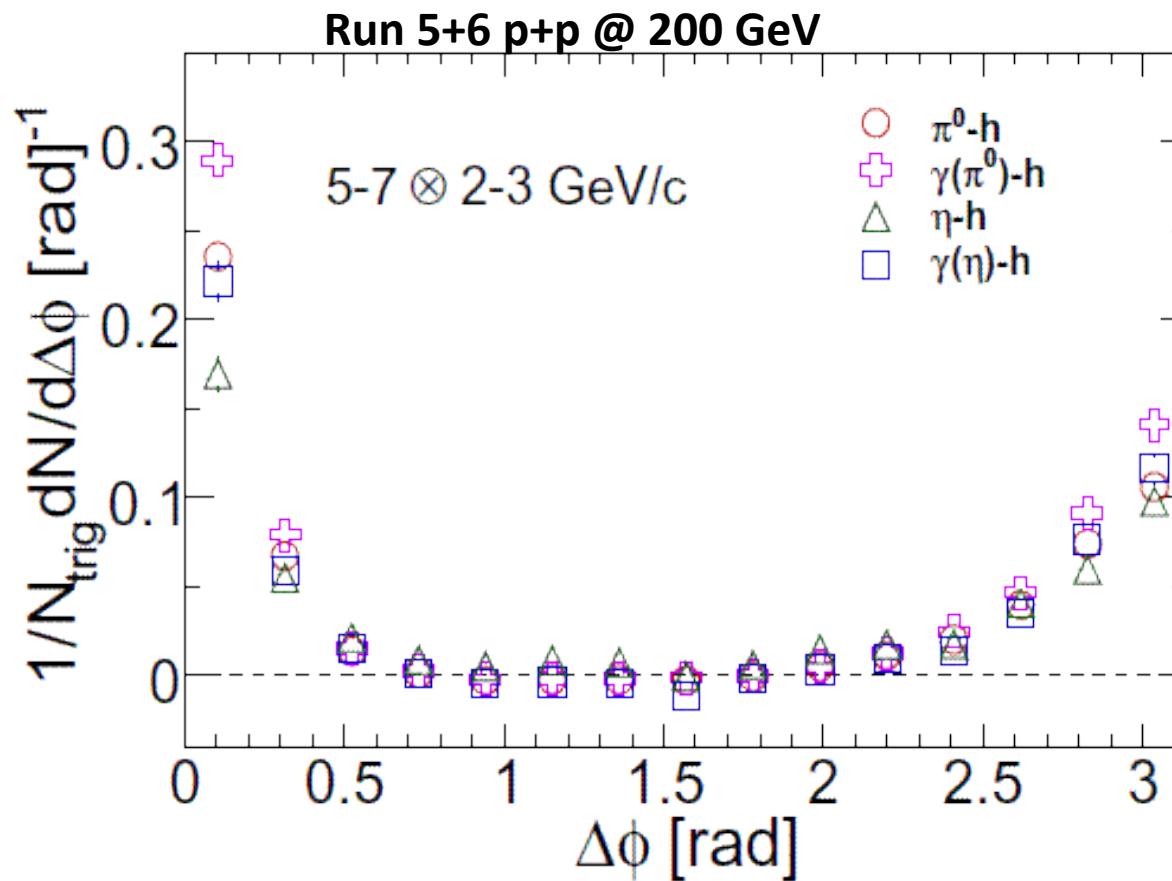
This question is serious. The phenomena are sufficiently complicated that it will be very difficult to figure out what is really going on. I think the venture of building and using a heavy-ion collider must be regarded as a calculated risk. The scientific output is not likely to look at all like what will exist in the proposals – for better or worse. But what might be the payoffs?

J.D. Bjorken

FERMILAB-Conf-83/070-T

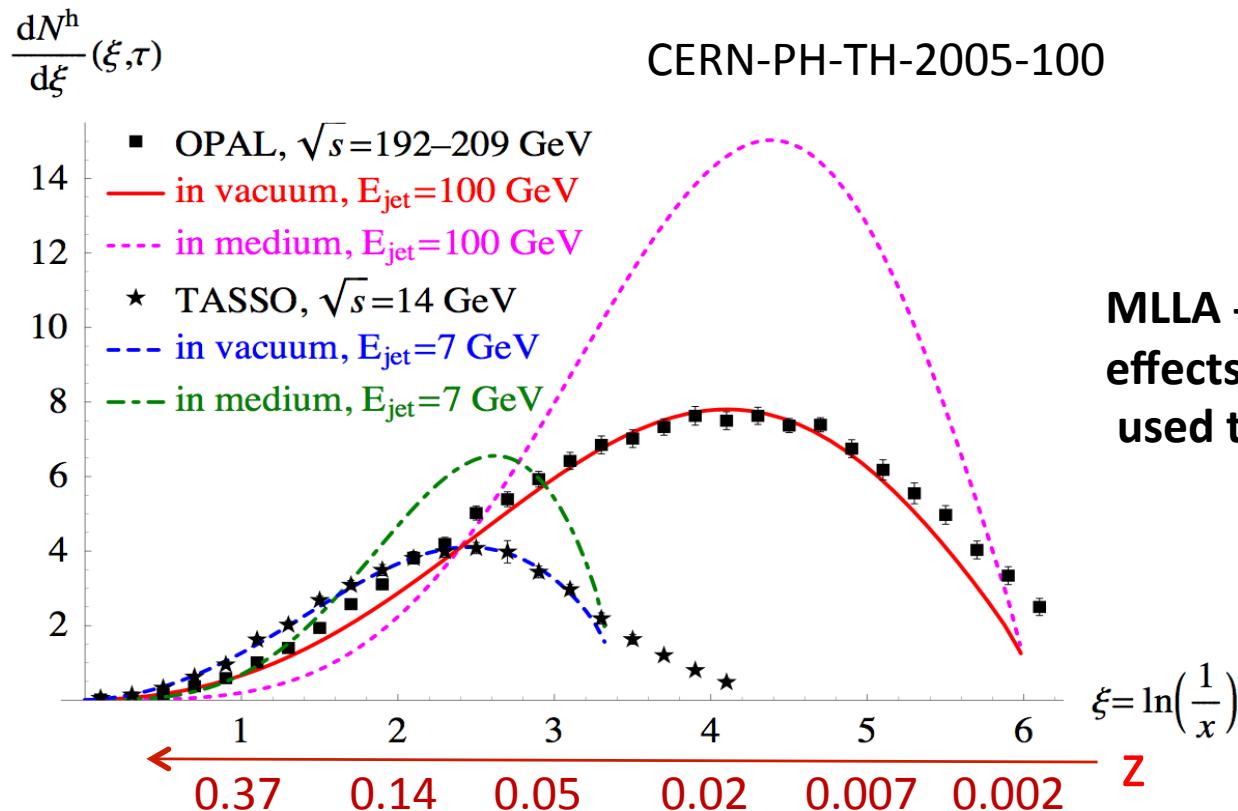
Backup Slides

Decay γ Correlations



- p+p: Directly measure $\pi^0\text{-}h$ and $\eta\text{-}h$, > 95% of decay contribution
- Parent \rightarrow daughter mapping determined from simulation
- Au+Au: Measure $\pi^0\text{-}h$, apply $\eta\text{-}h/\pi^0\text{-}h$ as a correction

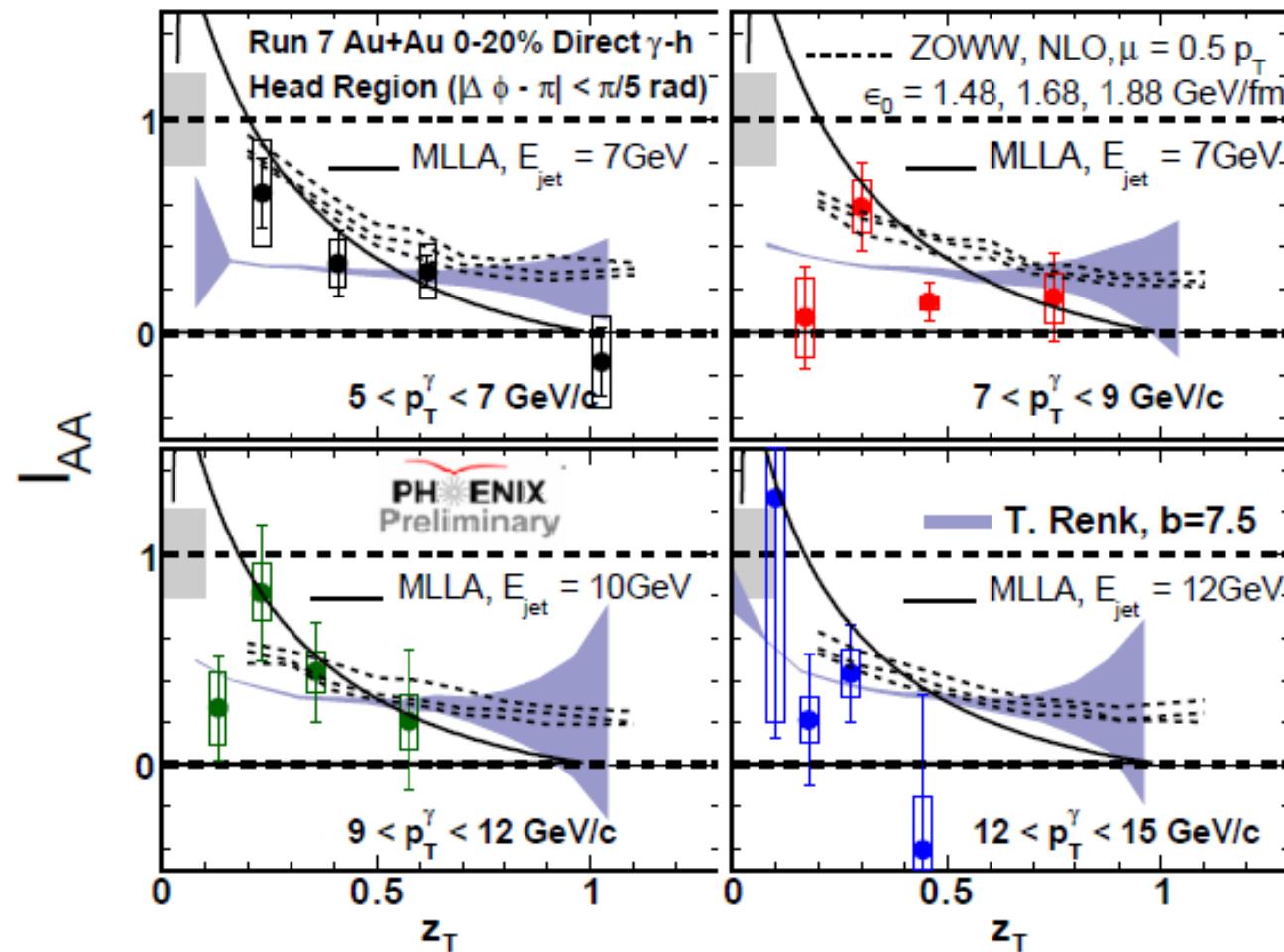
Modified Leading Log Approach



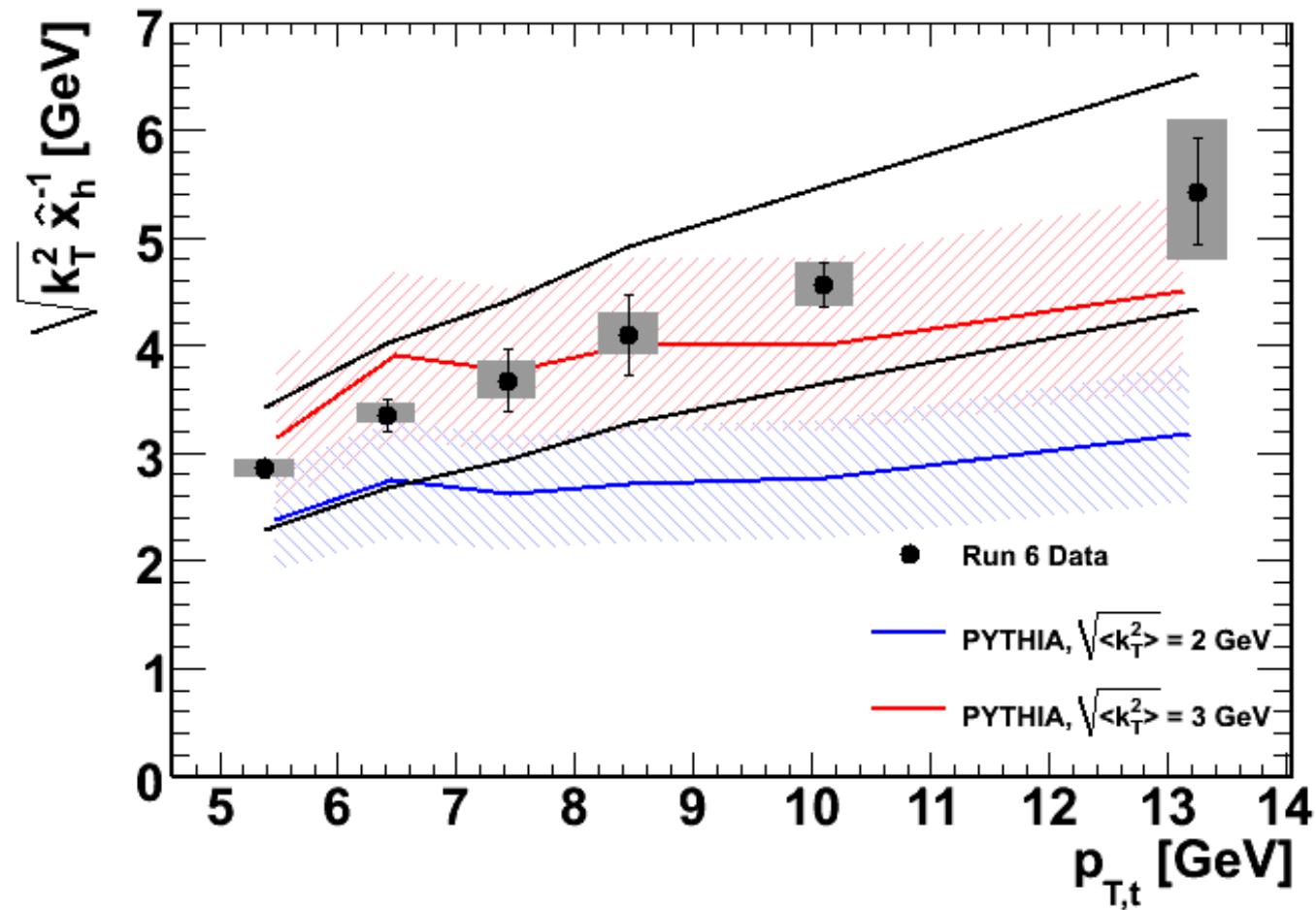
MLLA -- Resummation of interference effects in shower evolution, used to calculate $D(z)$ using LPHD

Very different than “fractional energy loss”, may be Q^2 dependent
Values of z at which enhancement are rather low, can this framework explain observed enhancement at large $\Delta\phi$ given realistic geometry and medium expansion? Two ways to compare to predictions for medium “FF’s” : Jet Reconstruction, direct γ triggered correlations

I_{AA} vs p_T



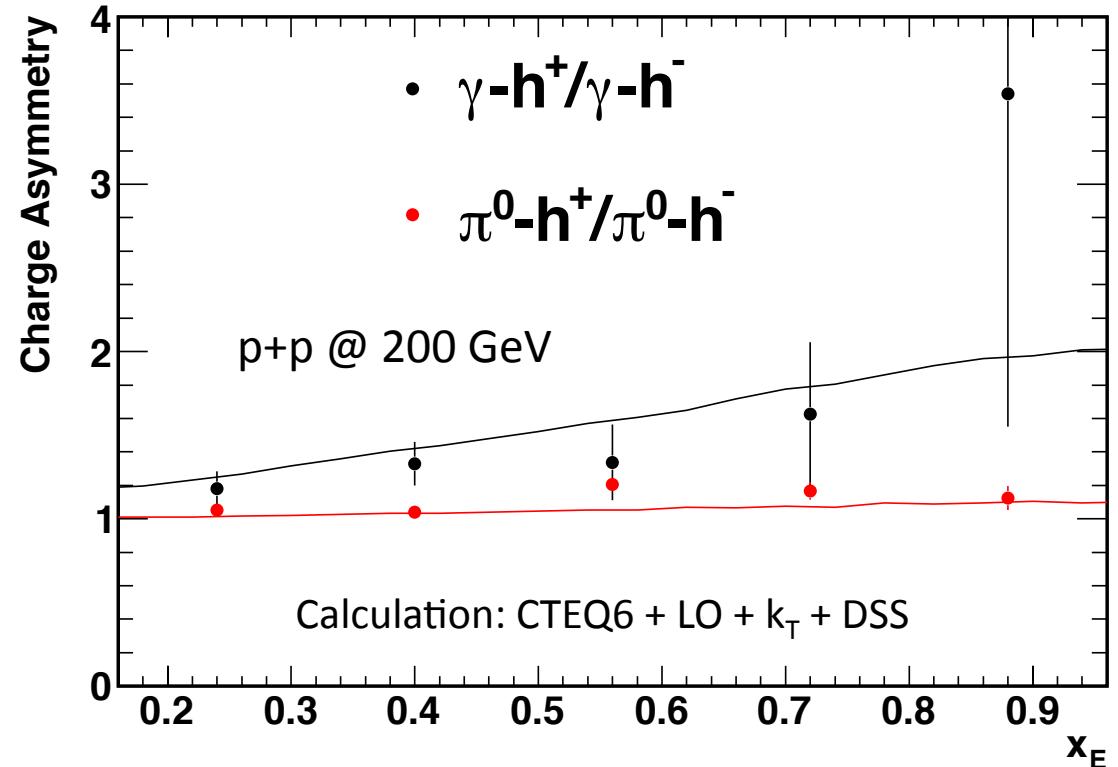
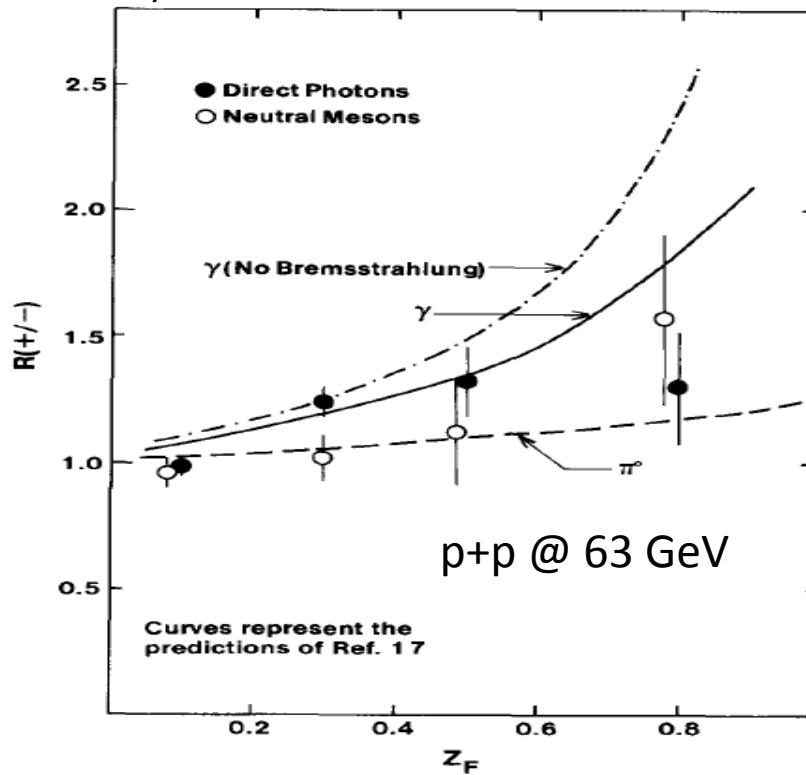
k_T for Isolated Directs γs



Charge Asymmetry

CMOR (ISR): NPB327 (1989) 541-568

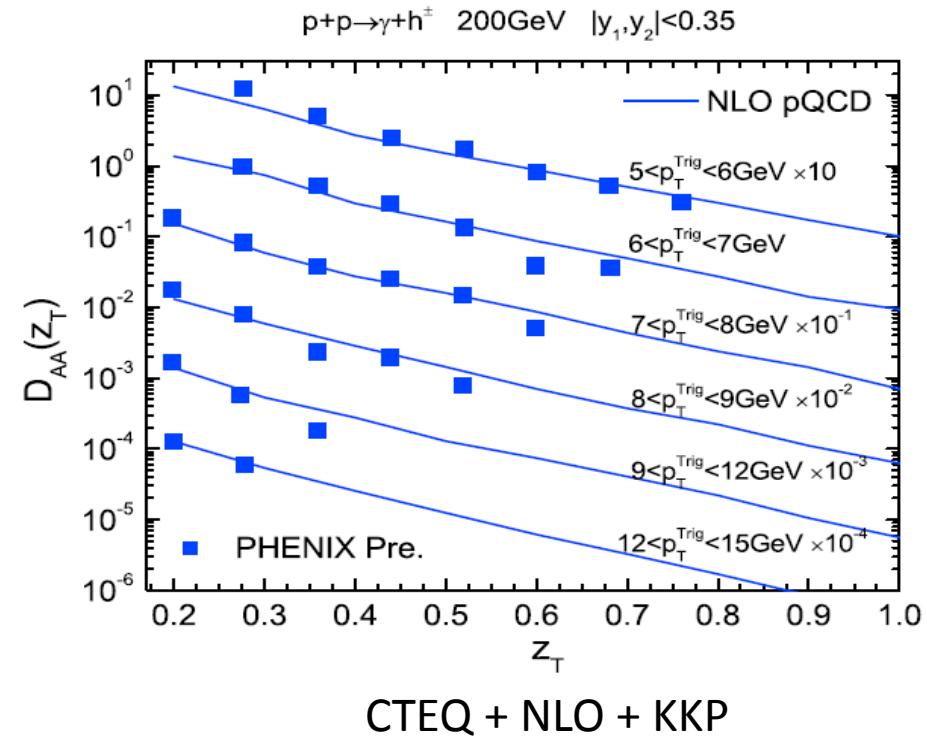
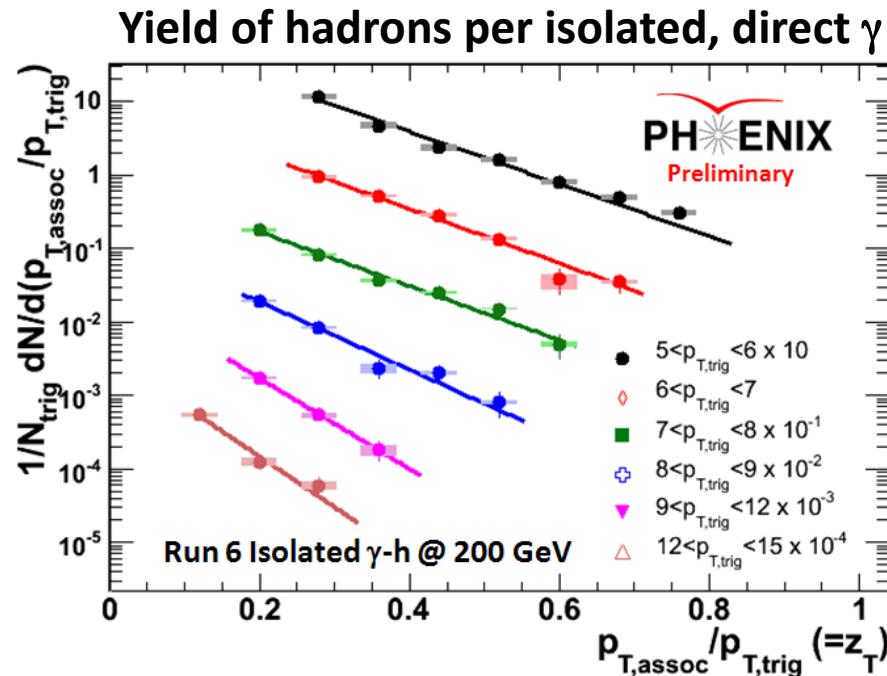
w/ NLO from Aurenche et. al



- Ratio of + to - charged hadrons for the away-side jet
- As $z \rightarrow 1$ pure Compton gives 8:1, but effect is diluted e.g., by k_T smearing
- Agreement w/ theory valuable check on $\gamma\text{-}h$ extraction method

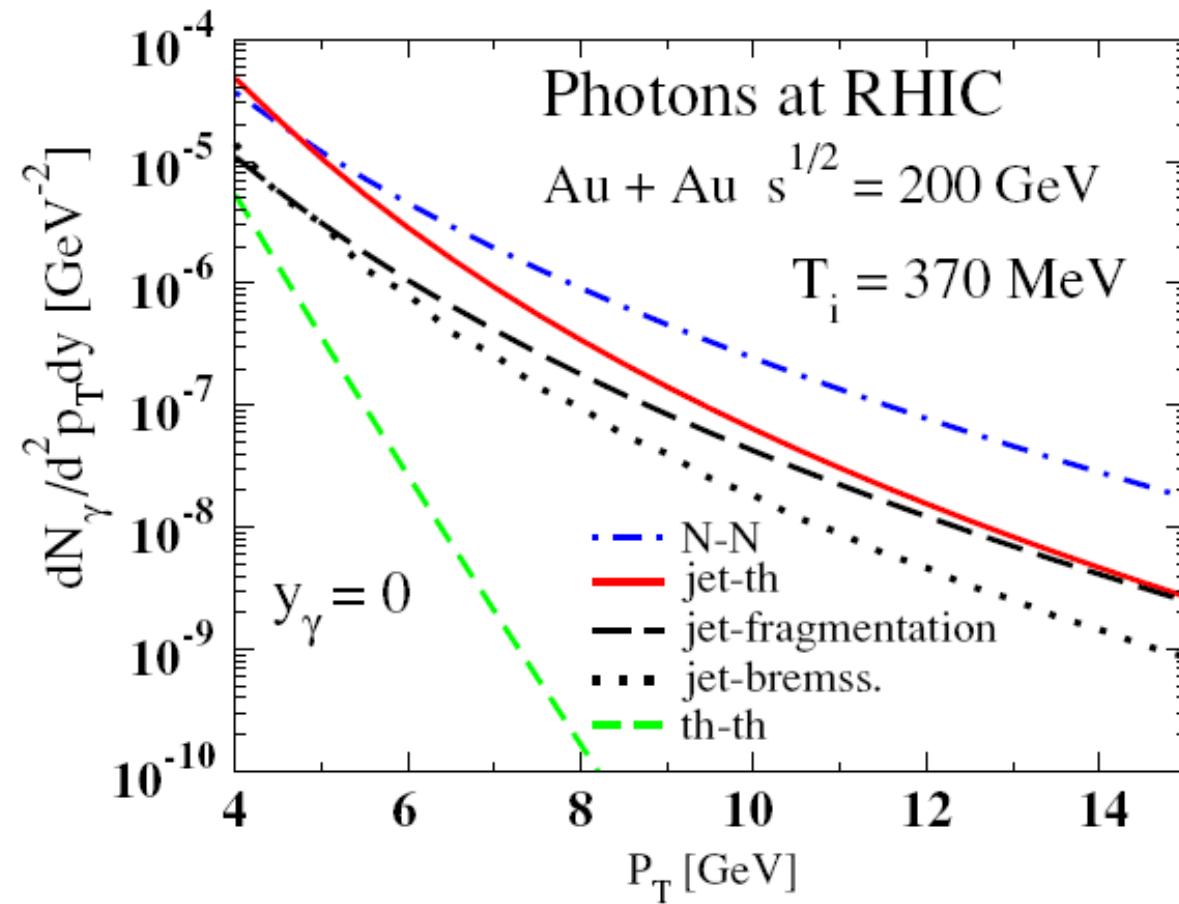
Isolated Direct γ Correlations

Zhang, Owens, Wang, Wang: arXiv:0902.4000

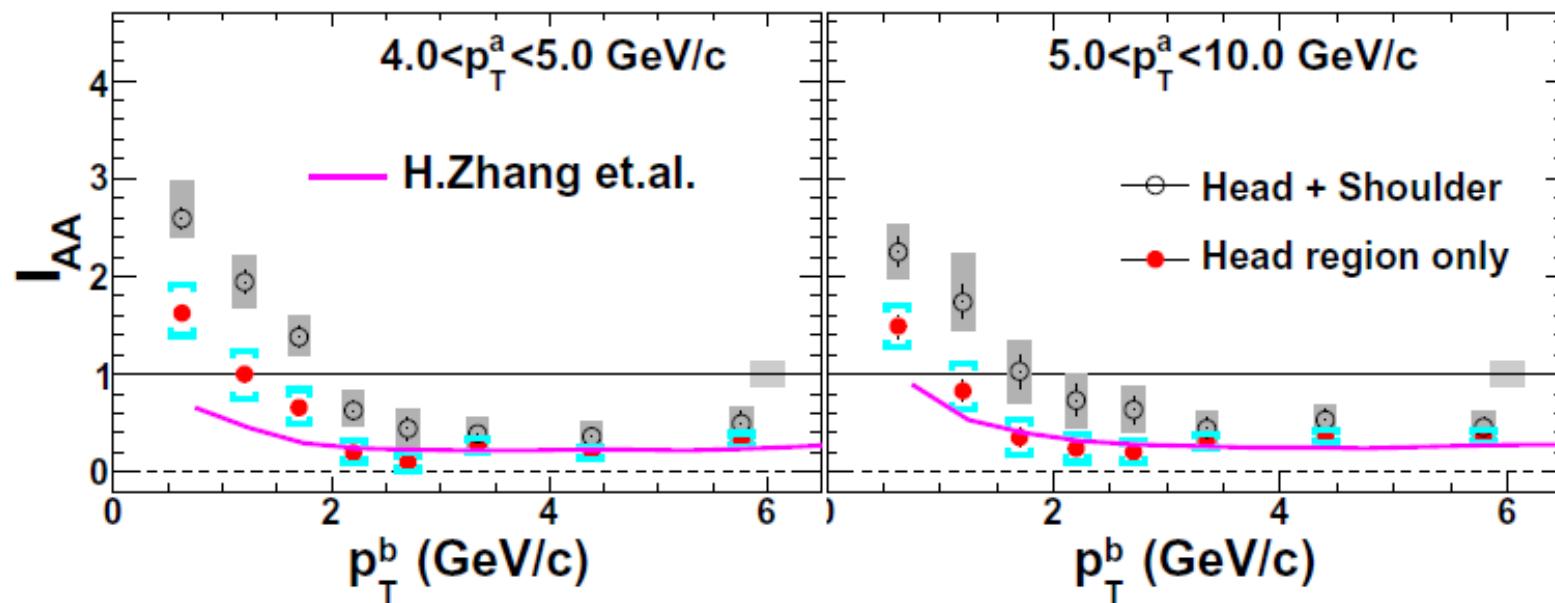
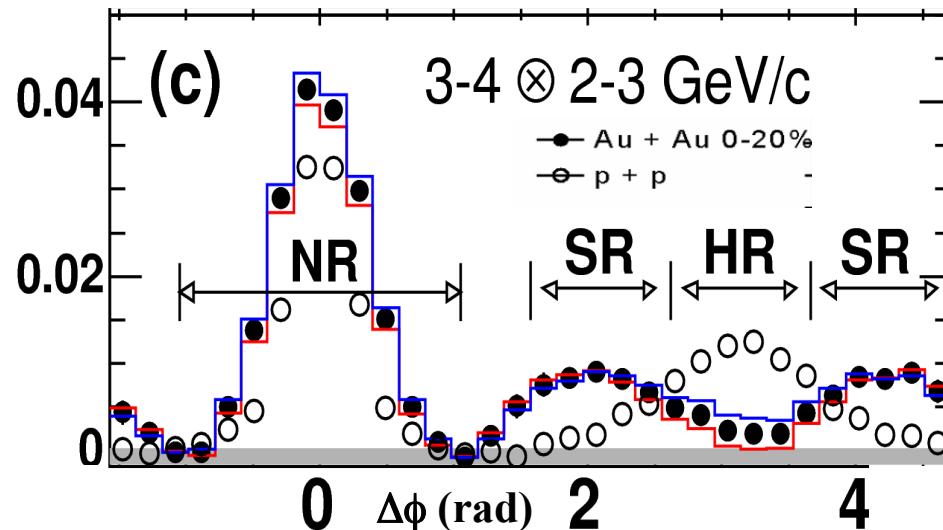


To first order $p+p$ baseline well described by NLO:
 Work being done to quantify scale uncertainties, sensitivity to k_T effect, etc.

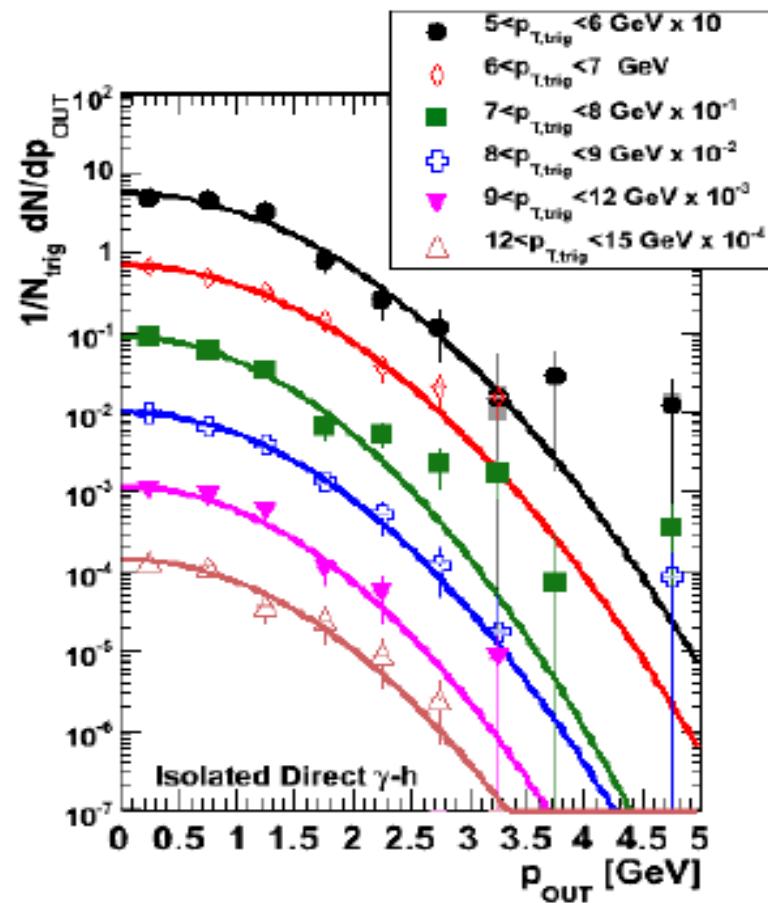
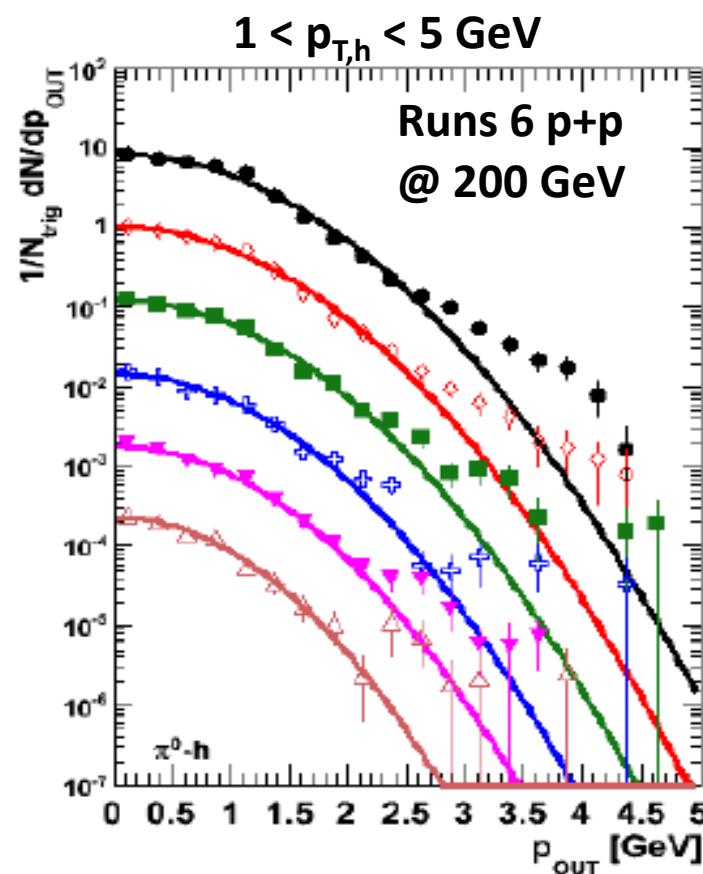
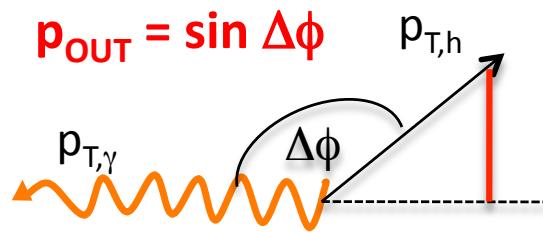
Photon Sources in Au+Au



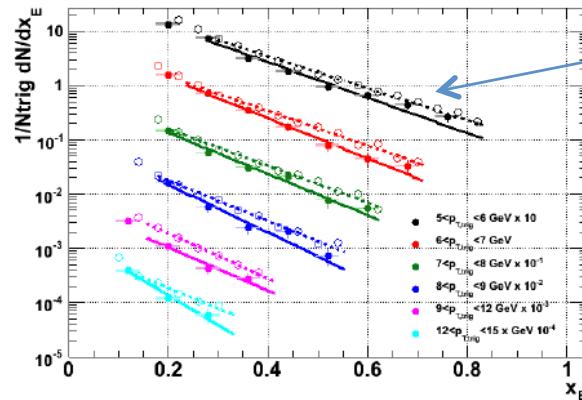
Di-hadron I_{AA}



p_{out} Distributions



Slope of π^0 Triggered x_E Dist.



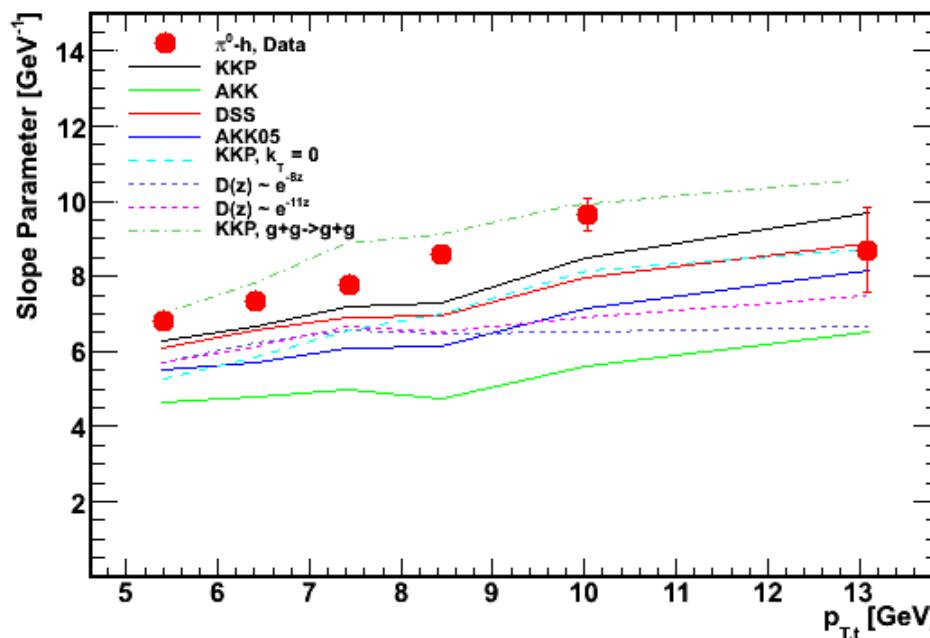
$\pi^0 = \text{open points}$

FF sets give a much larger spread in predictions.
KKP and DSS come closest

k_T matters although not as much as choice of FF set

Overall shape of FF doesn't matter, consistent with previous PHENIX measurement

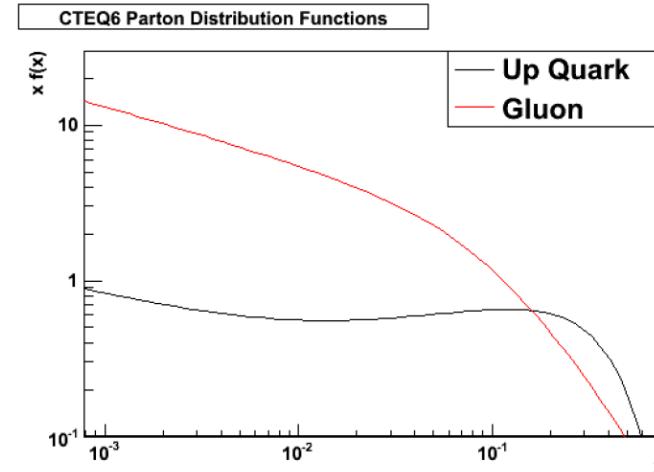
However, mix of processes does matter → relative shape of quark vs gluon FF matters



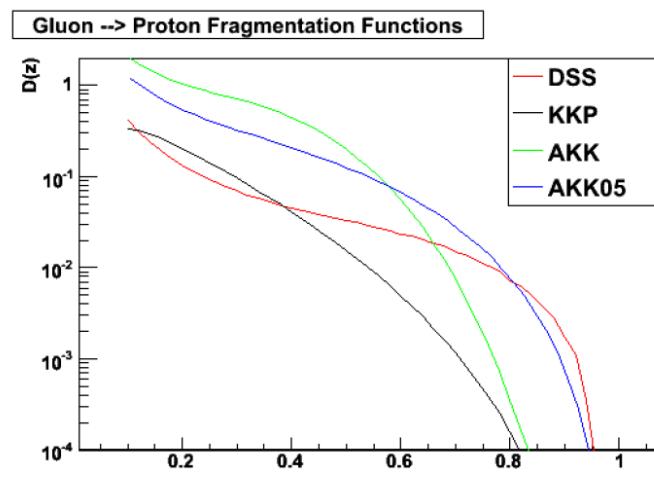
LO + k_T MC Generator

$$\frac{d^5\sigma}{dx_1 dx_2 d\cos\theta^* dz_3 dz_4} = \sum_{a,b,c,d} F_a(x_1) F_b(x_2) G(\vec{k}_T) \frac{\pi\alpha^2(Q^2)}{\hat{s}} \hat{\Sigma}_{a,b}(\cos\theta^*) D_c(z_3) D_d(z_4)$$

- Start with general expression for back-to-back two-particle cross section
- Using LO x-section parton-parton scattering processes summing over all flavor permutations
- Add Gaussian k_T/j_T smearing (only k_T shown)
- Using CTEQ6 PDFs
- Try different FFs (KKP, DSS, AKK05/08)

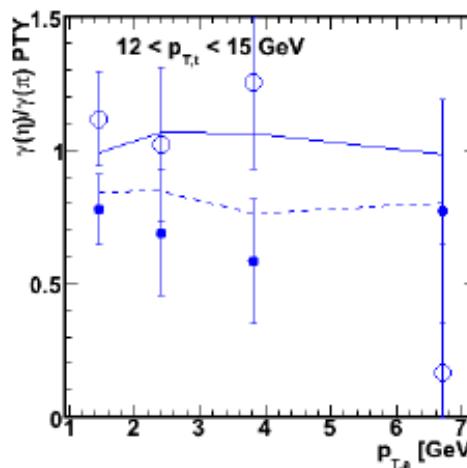
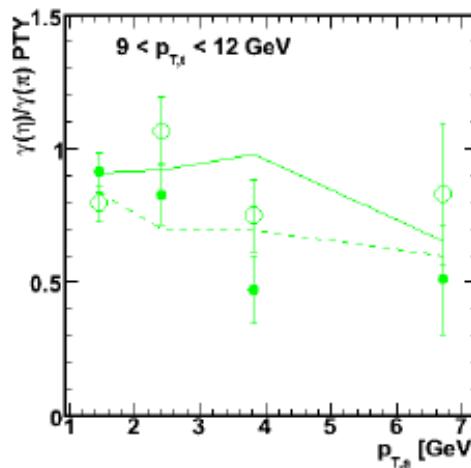
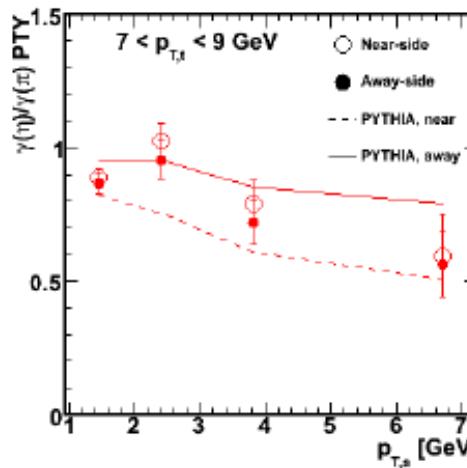
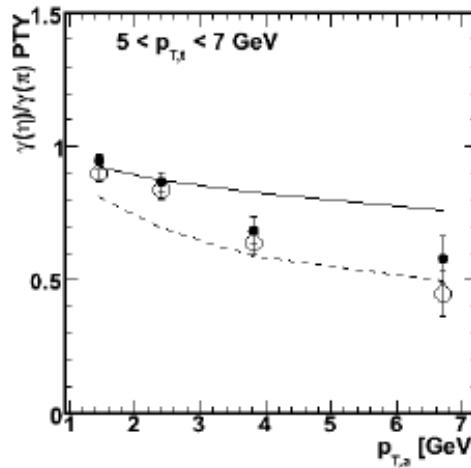


Examples of PDFs and FFs @ Q=7 GeV



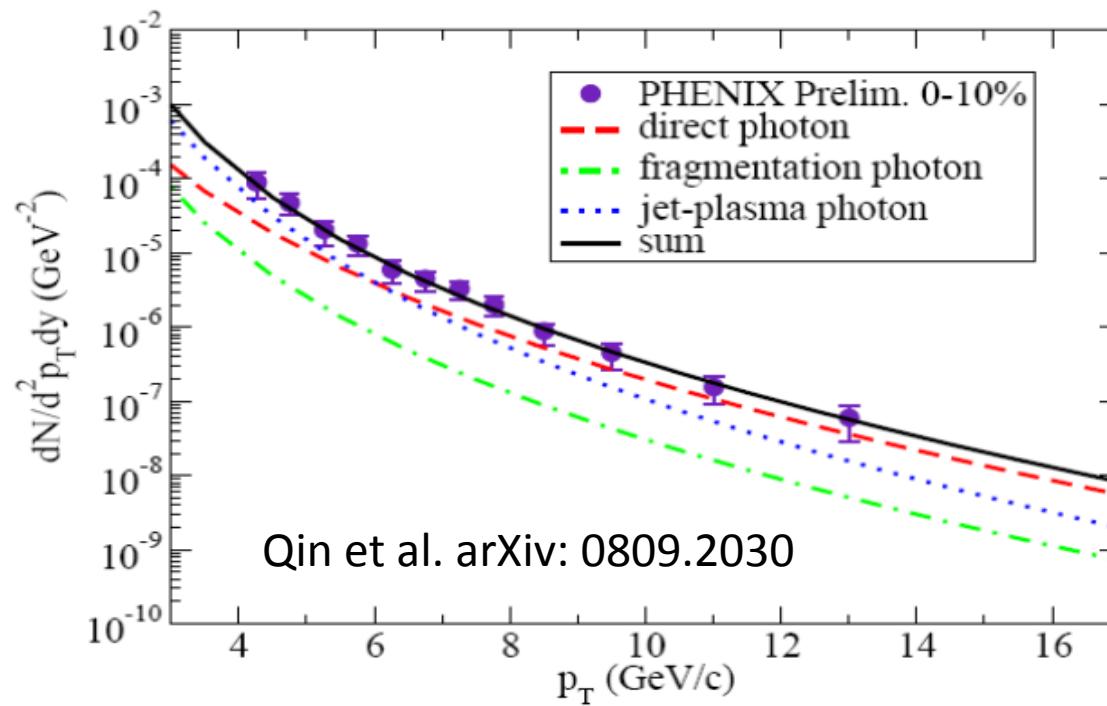
η Correlations

η -h/ π^0 -h



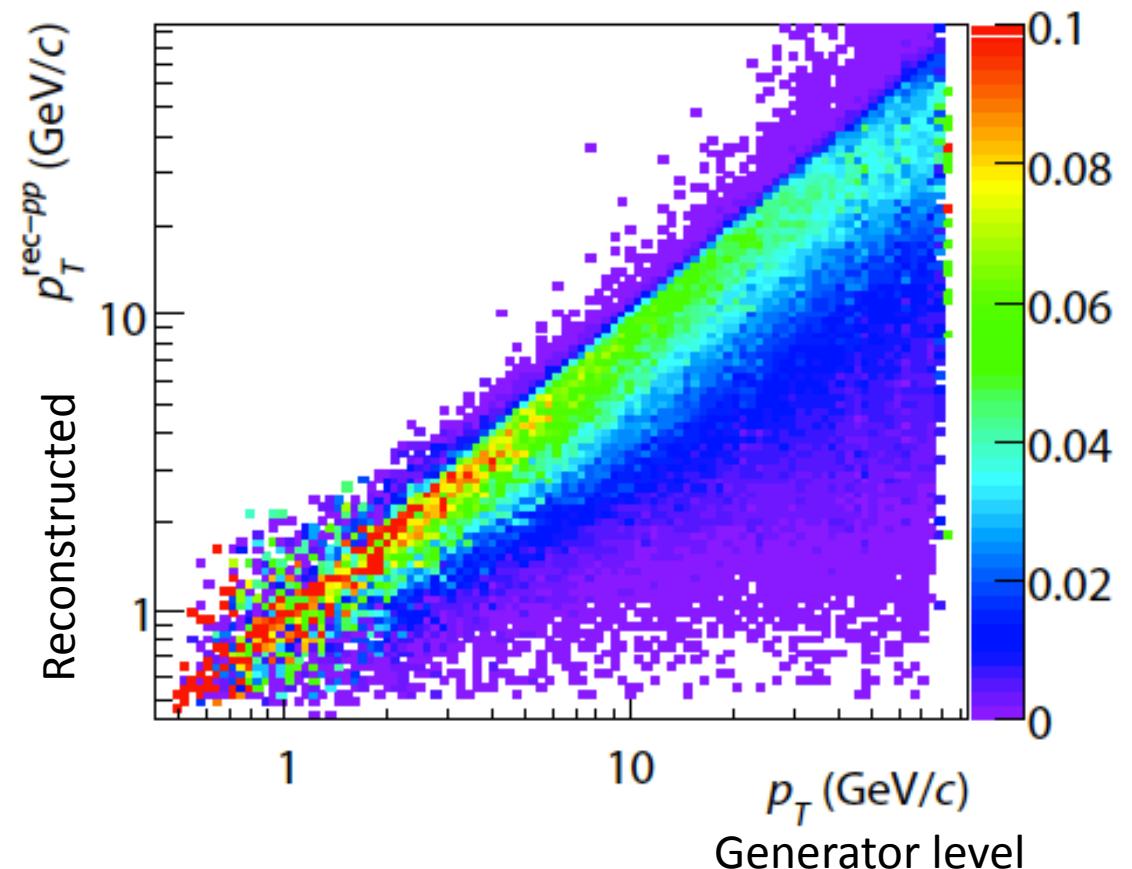
- η correlations are performed in p+p collisions
- False η matches are subtracted using the side-band correlations
- The procedure is checked in PYTHIA and found to give $\sim 10\%$ agreement between input and subtracted per-trigger yields which is assigned as the systematic error
- The ratio of the η to π^0 associated yields in p+p is applied as a correction factor in Au+Au where η correlations are not measurable
- The similar suppression pattern for η and π^0 supports this procedure

Medium-Induced γ Sources



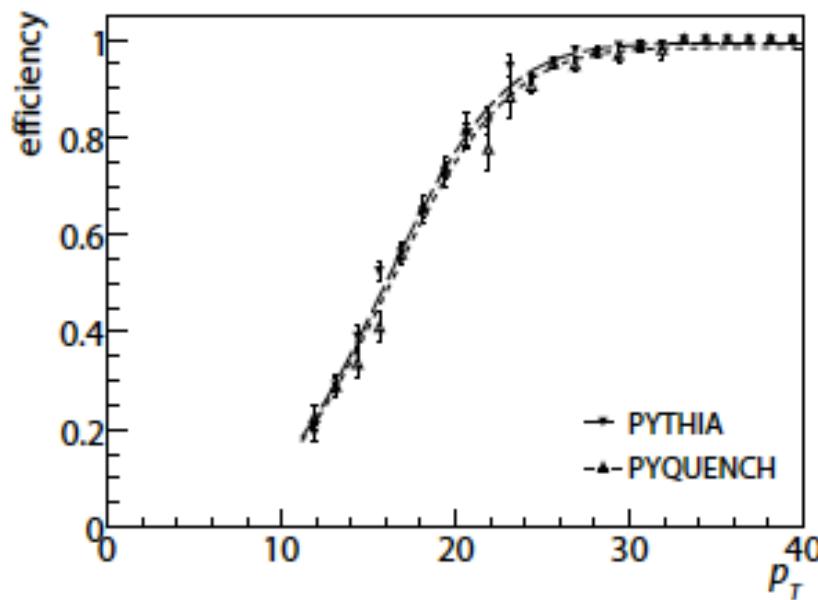
Jet Energy Scale in PHENIX

- Determined with PYTHIA/GEANT
- Unfolded with SVD using the GURU program
- Tails from conversions, neutrals (neutrons, K^0 , ...)
- Charged tracks restricted to $p_T < 25 \text{ GeV}/c$ due to background from conversions, decays



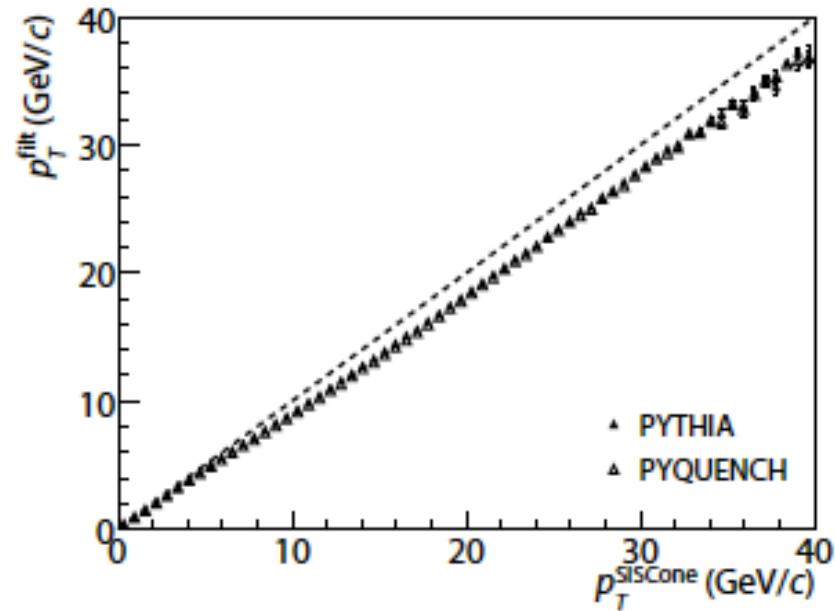
Fake rejection in PYQUENCH

- Fake rejection at $g'_{0.1} > 54 \text{ (GeV/c)}^2$ for central Au + Au.



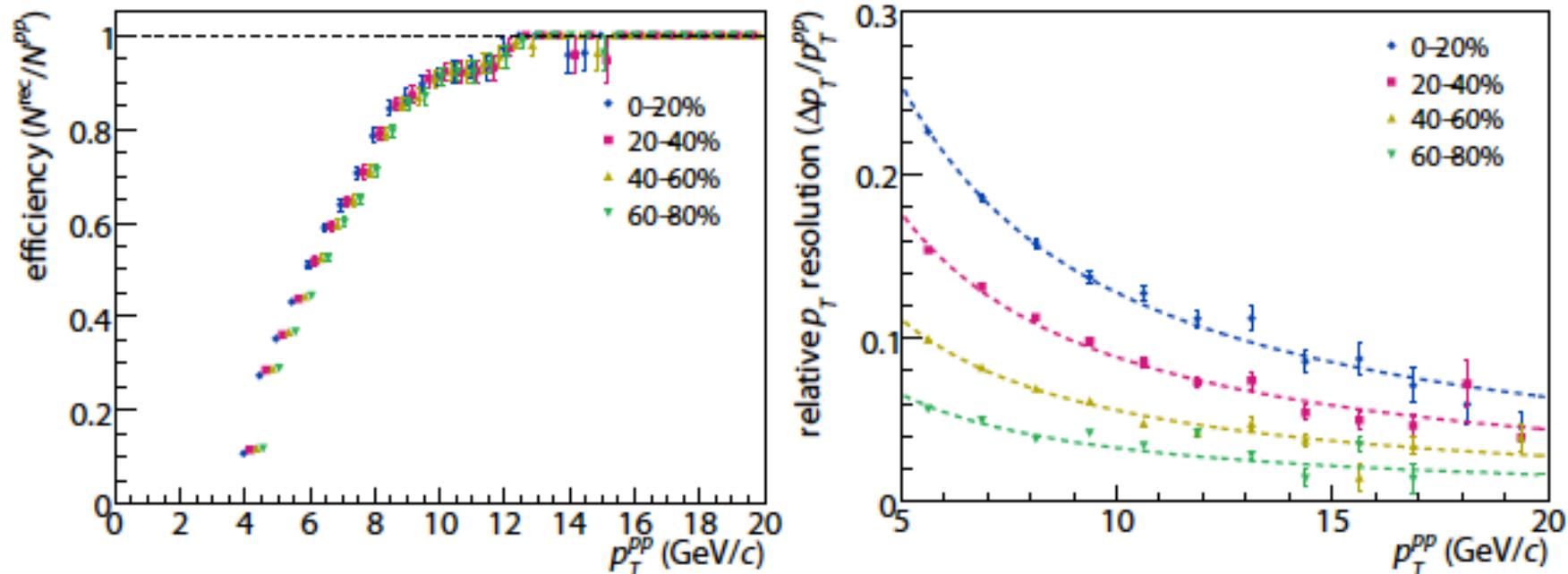
Efficiency turn-on after applying fake rejection

- Difference quenched vs. $p + p$ jets negligible (vs. our current systematics)
- Also observed by the ATLAS Collaboration (Grau *et al.*, arXiv:0810.1219, 2008)



Energy scale $\sigma = 0.3$ Gaussian filter against $R = 0.4$ SIScone

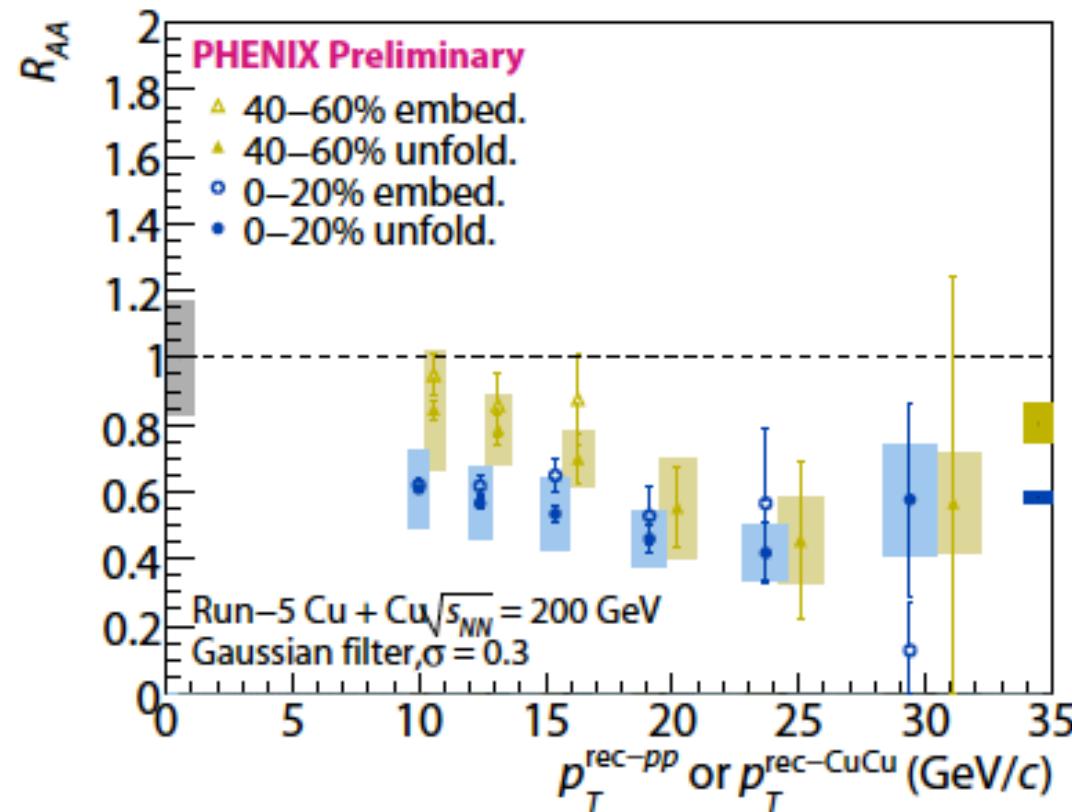
$p + p$ embedding in Cu + Cu: performance



Several desirable properties for heavy ion jet reconstruction:

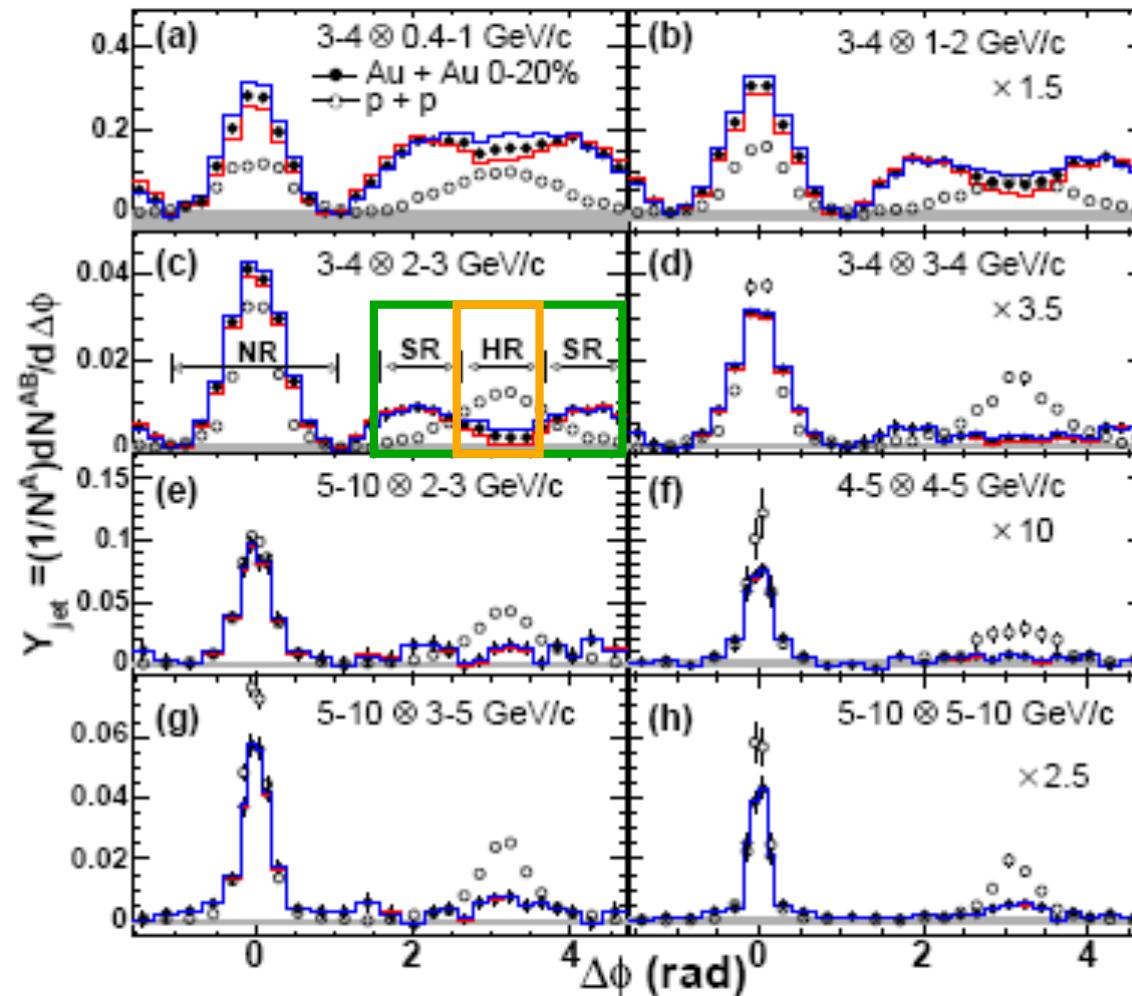
- Fast saturation to unitary efficiency
- **Negligible centrality dependence of jet reconstruction efficiency**
 - Efficiency includes the fake rejection

Run-5 Cu + Cu R_{AA} , $\sigma = 0.3$ compared to embedding



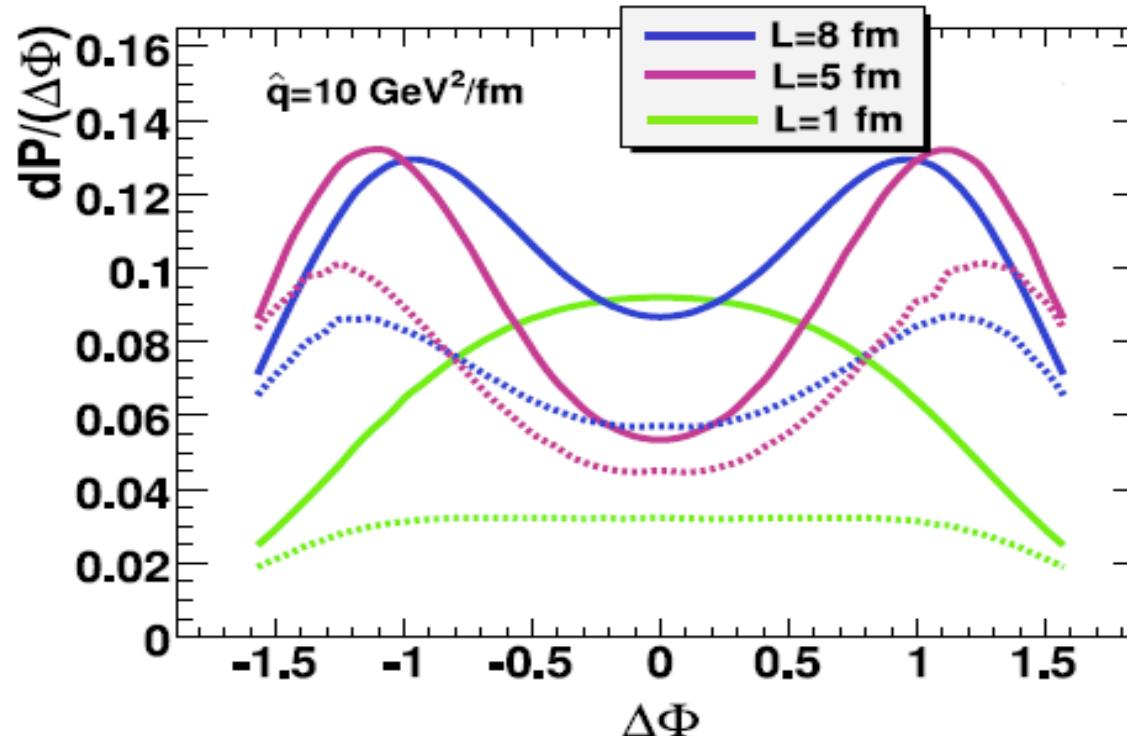
- Unfolded: uncorrected $p + p$ compared to background-unfolded Cu + Cu
- Embedded: uncorrected Cu + Cu compared to embedded $p + p$
- Mismatching energy scale, but R_{AA} is roughly flat

Away-side: head vs shoulder



Modified Jet Shapes from Modified pQCD

Polosa and Salgado, PRC75, 041901 (2007)



- Using standard perturbative methods (**Sudakov Form Factors**) calculates shower evolution
- Introduce modified splitting functions to account for multiple scattering in medium
- Large angle scattering is enhanced, reproducing conical emission

Interpreting Two-Particle Correlations

- Two-Particle correlations rely on estimate of the underlying event
- In heavy-ion collisions, UE modulated due to initial asymmetry of overlap region
- How to factorize UE from jets in presence of medium response?
- Di-hadron correlations frustratingly difficult to model
 - Jet selection biased by trigger particle
 - Also gives geometrical bias
 - Initial parton energy unknown
- Need observables for which initial parton energy can be determined and the path-length dependence can be modeled
 - Fully reconstructed jets
 - Direct photon tagged jets, correlations

